Forum for Electromagnetic Research Methods and Application Technologies (FERMAT)

Graphene Magnetoplasmonic Principles, Structures and Devices

Nima Chamanara and Christophe Caloz

Poly-Grames Research Center, Montreal, QC, Canada

Abstract:

This paper recalls fundamentals of magnetoplasmons in magnetically biased graphene structures, describes their non-reciprocity and demonstrates their utilization as devices such as isolators and couplers. A multi-scale multi-physics structure, using a magnetic nanowire membrane as integrable magnetic bias, with applications to Faraday rotators and integrable nonreciprocal plasmonic components, is presented.

Keywords: graphene, plasmonics, magnetoplasmon, nonreciprocity, isolator, coupler.

References:

[1] N. Chamanara, D. L. Sounas, and C. Caloz, "Nonreciprocal magnetoplasmon graphene coupler," Opt. express., vol. 21, no. 9, pp. 11248–11256, 2013.

[2] N. Chamanara, D. L. Sounas, T. Szkopek and C. Caloz, "Optically transparent and flexible graphene reciprocal and nonreciprocal microwave planar components". IEEE Microw. Wireless Comp. Lett, , vol. 22, no. 7, pp. 360-362, 2012.

[3] N. Chamanara, D. L. Sounas, and C. Caloz, "Nonreciprocity with graphene magnetoplasmons and application to plasmonic isolators," in Electromagnetic Theory (EMTS), Proceedings of 2013 URSI International Symposium on, pp. 266–268, IEEE, 2013.

[4] N. Chamanara, D. L. Sounas, T. Szkopek, and C. Caloz, "Terahertz magnetoplasmon energy concentration and splitting in graphene pn junctions," Opt. express, vol. 21, no. 21, pp. 25356–25363, 2013.

[5] N. Chamanara and C. Caloz, "Multiscale and Multiphysics Graphene Sheet – Magnetic Nanowire Gyrotropic Metamaterial," in AP-S Int. Antennas Propagat. (APS), 2014.

This use of this work is restricted solely for academic purposes. The author of this work owns the copyright and no reproduction in any form is permitted without written permission by the author.

Graphene Magnetoplasmonic Principles, Structures and Devices

Nima Chamanara*and Christophe Caloz*†

* École Polytechnique de Montréal, Canada

† King Abdulaziz University, Jeddah, Saudi Arabia

9th European Conference on Antennas and Propagation
Lisbon, Portugal | 12-17 April 2015 | www.eucap2015.org
European Association on Antennas and Propagation

Outline

I. Introduction to graphene magnetoplasmons

II. Principles of Non-reciprocity

III. Structures and Devices

- I. Nonreciprocal Phase Shifter
- II. Non-reciprocal Coupler
- III. Magnetoplasmonic Isolators
- IV. Magnetic Sensor

❖ Conclusions & Questions

Outline

I. Introduction to graphene magnetoplasmons

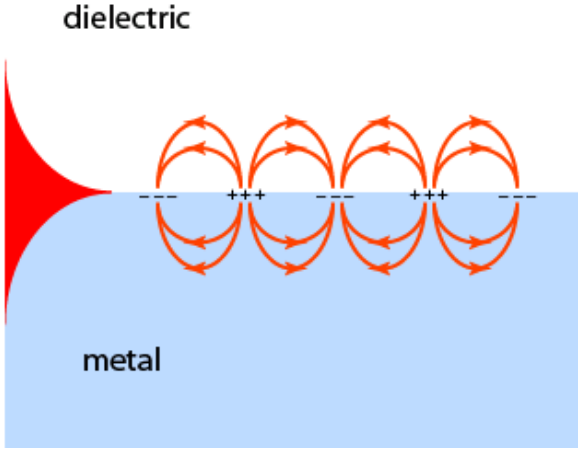
II. Principles of Non-reciprocity

III. Structures and Devices

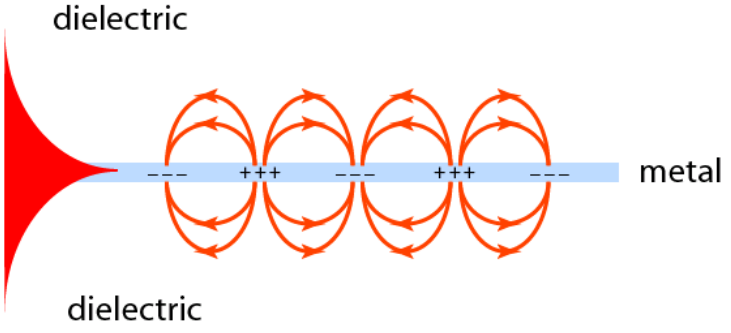
- I. Nonreciprocal Phase Shifter
- II. Non-reciprocal Coupler
- III. Magnetoplasmonic Isolators
- IV. Magnetic Sensor

❖ Conclusions & Questions

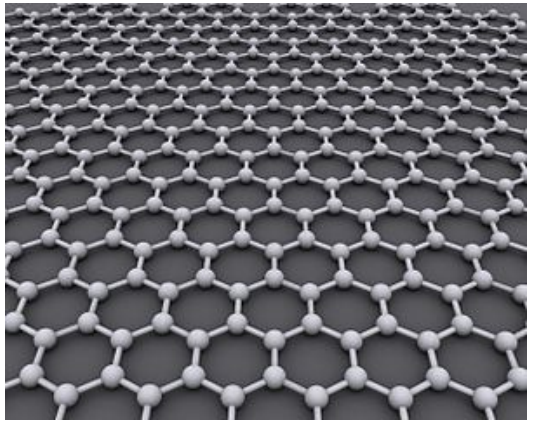
Surface Plasmons - Introduction



metal-dielectric interface



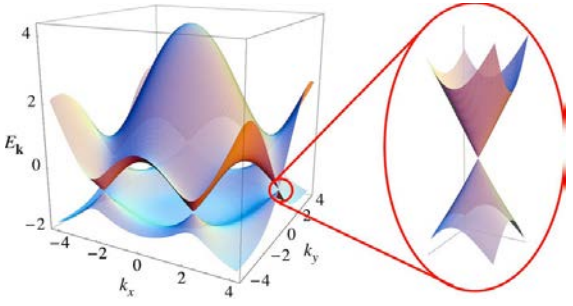
2D electron gas (2DEG)



graphene

graphene:

- one atom thick material
- gapless energy band
- 2D electron system with high mobility
- tunability and ambipolarity



C. Neto et al., *Rev. Mod. Phys. 81, 109 –January 2009*

Plasmons and Magnetoplasmons in an Infinite Graphene Sheet

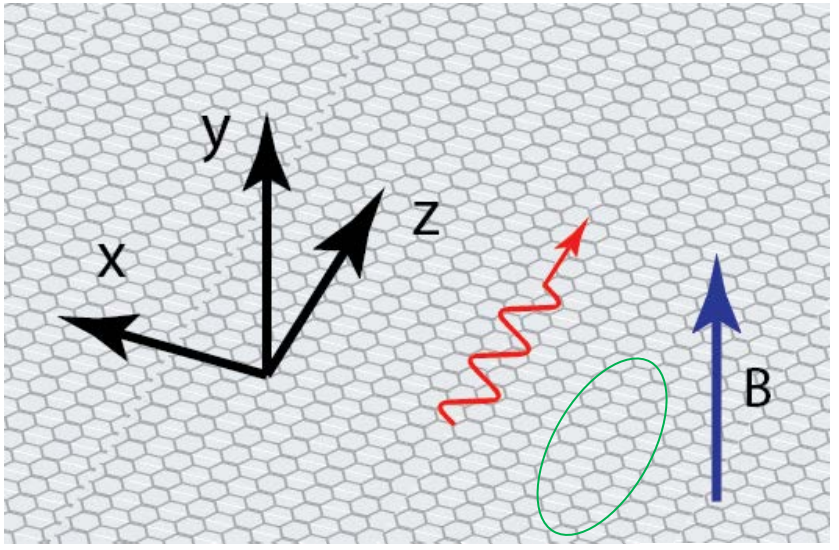
$\mathbf{B}_0 = 0$

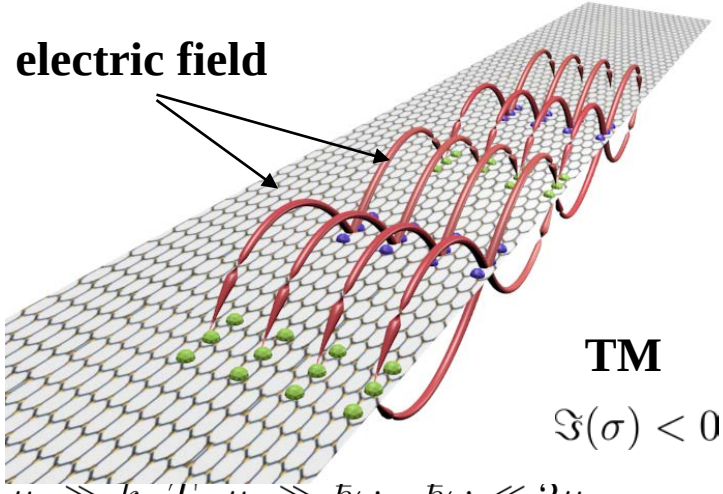
$\Im(\sigma) < 0 \quad \Rightarrow \quad$ longitudinal (TM_z)

$\Im(\sigma) > 0 \quad \Rightarrow \quad$ transverse (TE_z)

$\mathbf{B}_0 > 0$

$\Rightarrow \quad$ hybrid mode





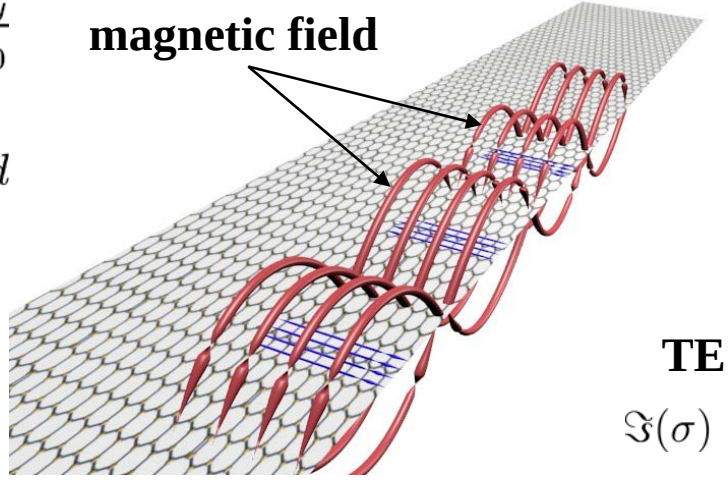
TM

$\Im(\sigma) < 0$

$\mu_c \gg k_B T$, $\mu_c \gg \hbar\omega_c$, $\hbar\omega \ll 2\mu_c$

$\frac{a_y}{k_0}$

s_d

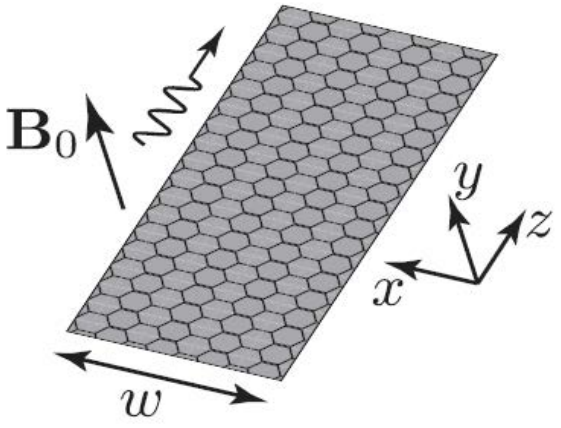


TE

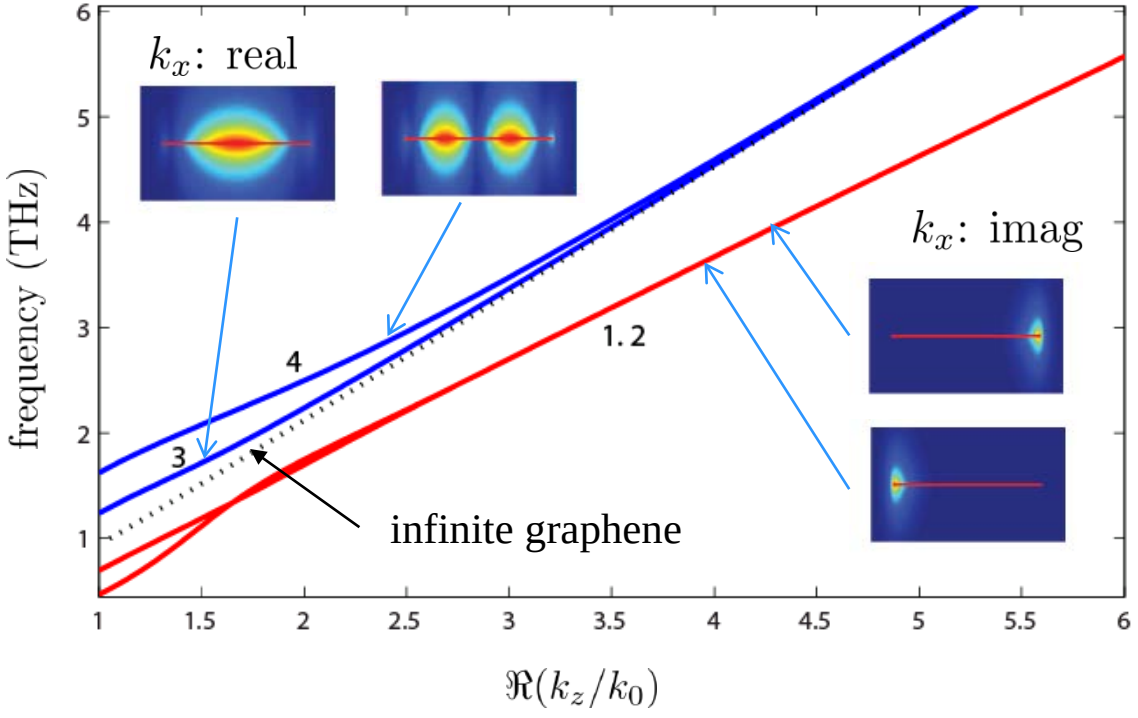
$\Im(\sigma) > 0$

Plasmons in a Graphene Strip

graphene strip without magnetic bias
- 2D eigenvalue problem
- finite difference frequency domain (FDFD)
- graphene: zero thickness conductive strip
- Kubo conductivity tensor
- infinite number of 2D bulk modes
- 2 degenerate edge modes



$$B_0 = 0$$



$n_s = 10^{13}$ cm^{-}2
$\tau = 0.1$ ps
$w = 100$ μm

Outline

I. Introduction to graphene magnetoplasmons

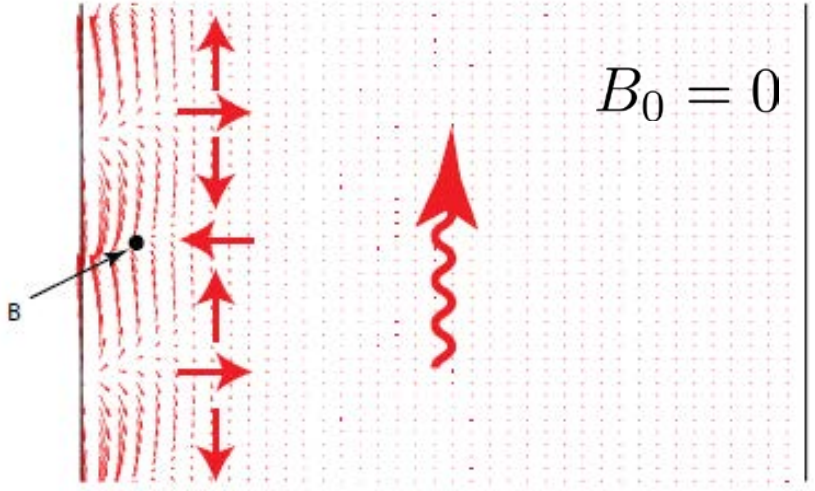
II. Principles of Non-reciprocity

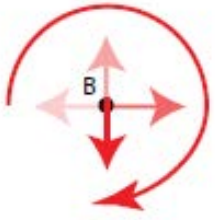
III. Structures and Devices

- I. Nonreciprocal Phase Shifter
- II. Non-reciprocal Coupler
- III. Magnetoplasmonic Isolators
- IV. Magnetic Sensor

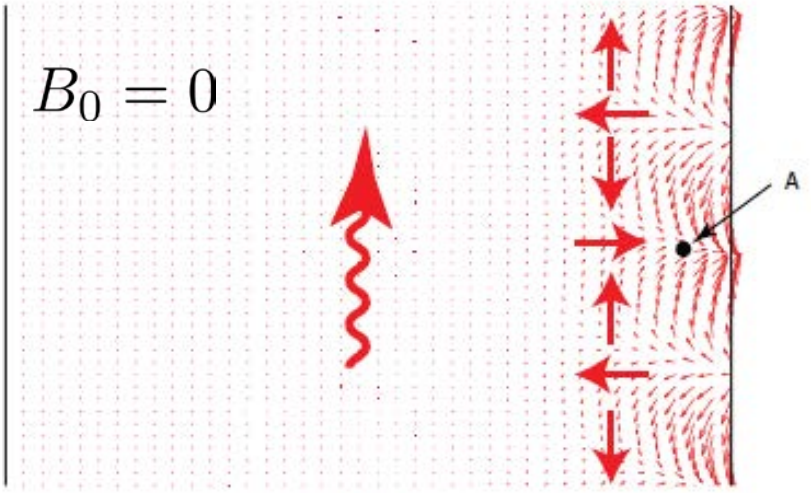
❖ Conclusions & Questions

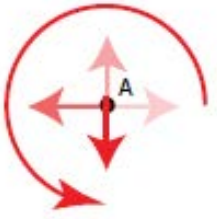
Splitting of the Edge Modes with a Magnetic Bias





(b)





(a)

$$\sigma = \sigma_d - j\sigma_o$$

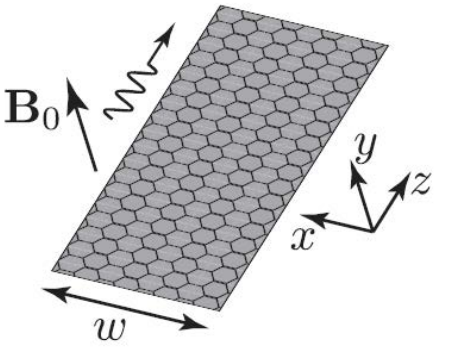
$$\sigma = \sigma_d + j\sigma_o$$

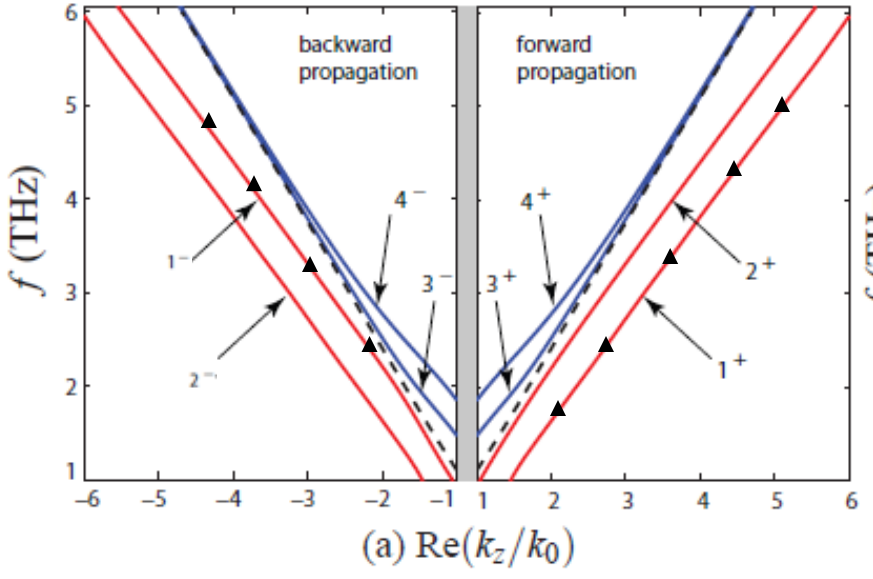
$$B_0 \uparrow \longrightarrow \bar{\bar{\sigma}} = \sigma_d(\hat{\mathbf{x}}\hat{\mathbf{x}} + \hat{\mathbf{z}}\hat{\mathbf{z}}) + \sigma_o(\hat{\mathbf{x}}\hat{\mathbf{z}} - \hat{\mathbf{z}}\hat{\mathbf{x}})$$

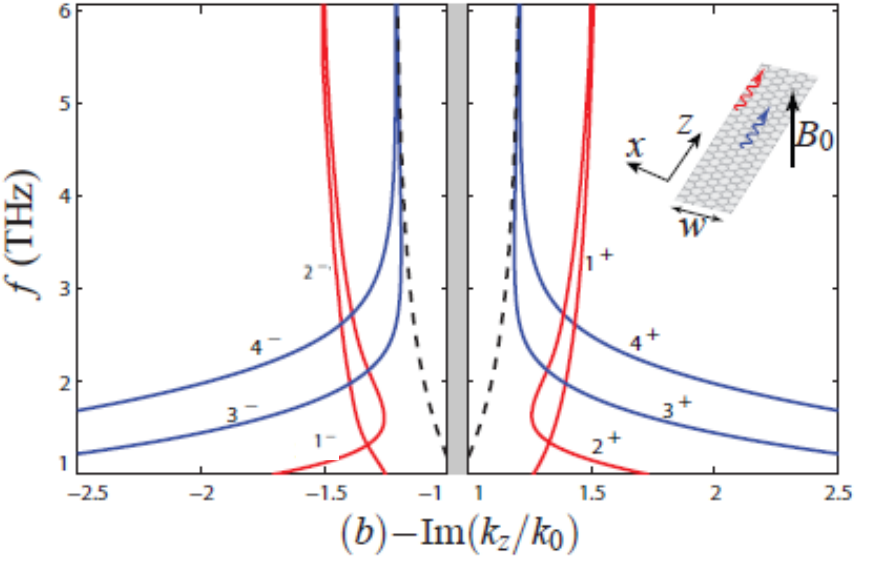
N. Chamanara, D. Sounas, and C. Caloz, *Opt. express., vol. 21, no. 9, pp. 11248–11256,* 2013.

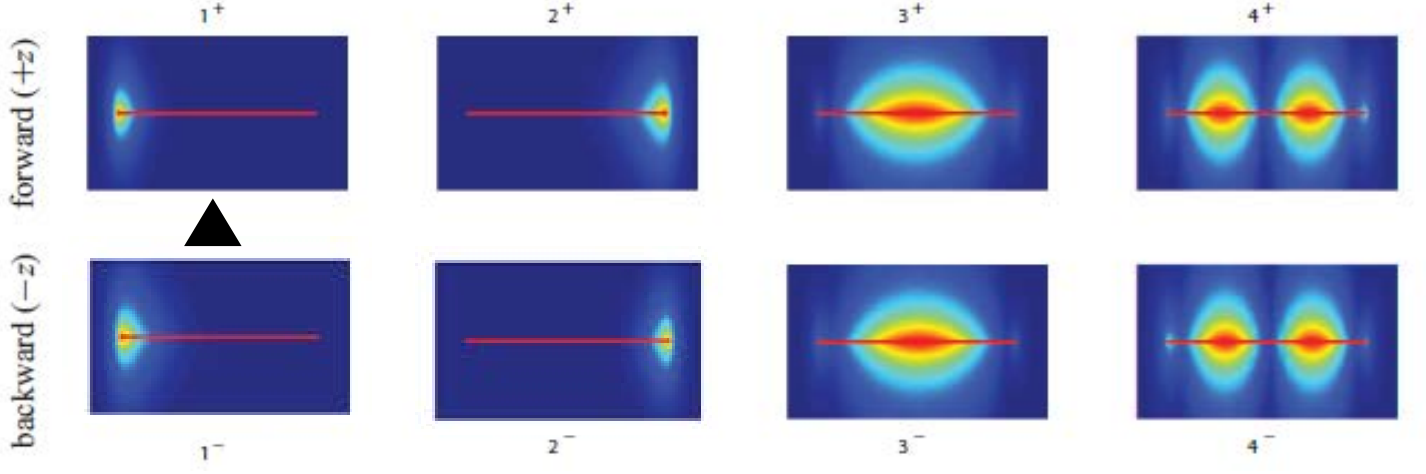
Magnetically Biased Graphene Strip

Edge modes
- split in a magnetic field
- exhibit non-reciprocal properties









$n_s = 10^{13}$ cm$^{-}2$
$\tau = 0.1$ ps
$w = 100$ μm
$B = 1$ T

Outline

I. Introduction to graphene magnetoplasmons

II. Principles of Non-reciprocity

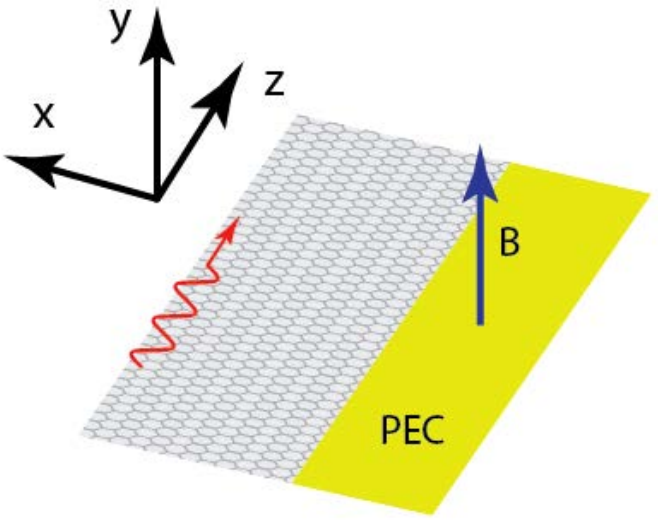
III. Structures and Devices

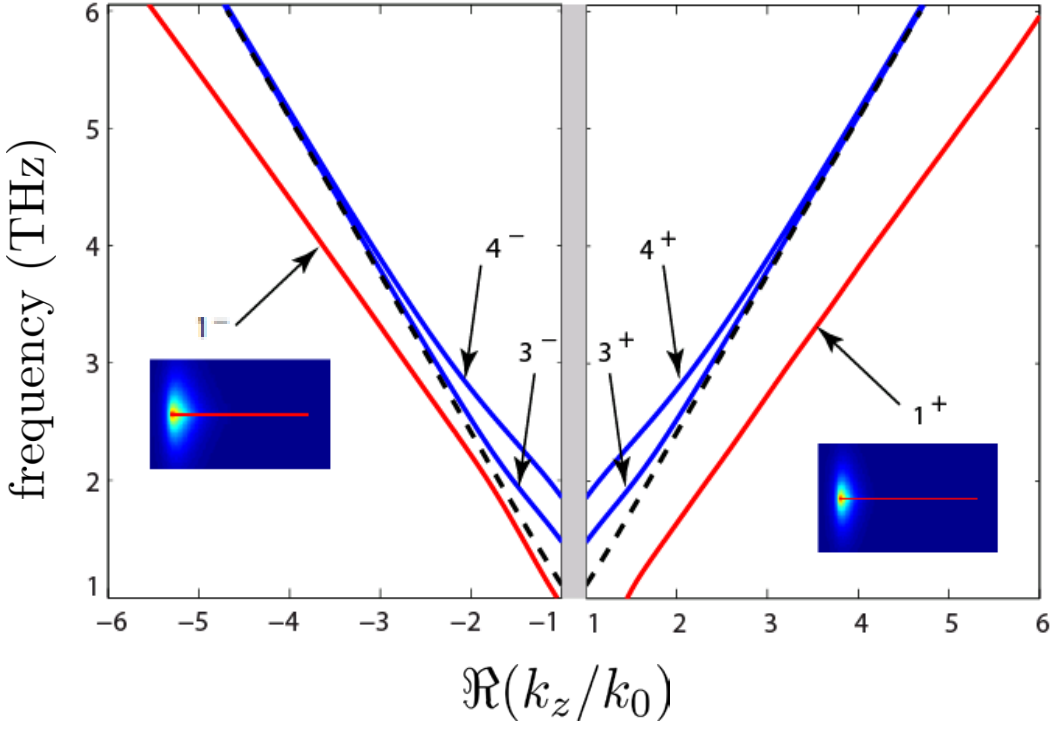
- I. Nonreciprocal Phase Shifter
- II. Non-reciprocal Coupler
- III. Magnetoplasmonic Isolators
- IV. Magnetic Sensor

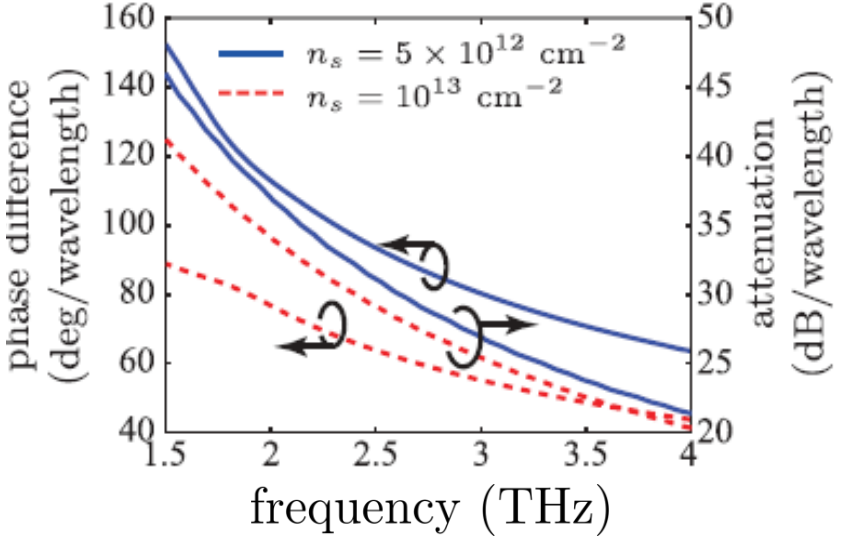
❖ Conclusions & Questions

Nonreciprocal Plasmonic Phase Shifter

Edge modes
- unsymmetric disperson for opposite directions
- ⇒ different phase shifts







Outline

I. Introduction to graphene magnetoplasmons

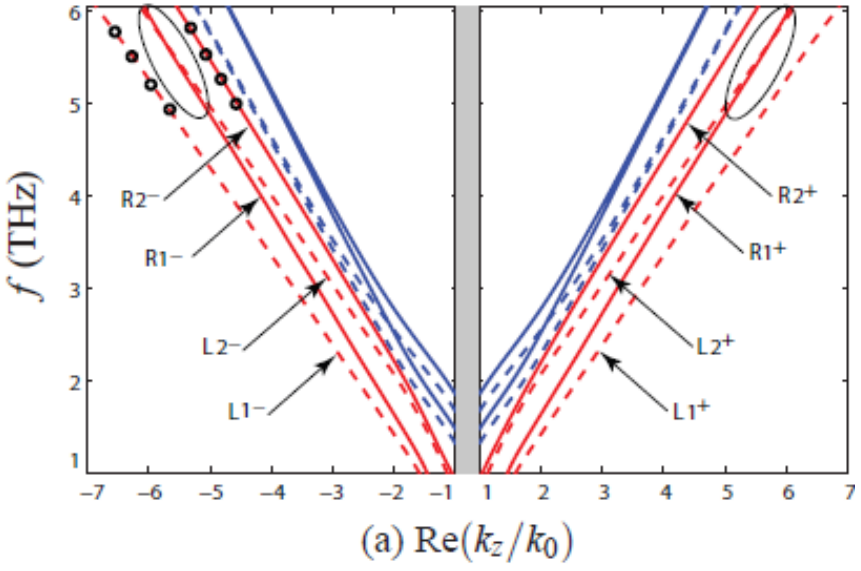
II. Principles of Non-reciprocity

III. Structures and Devices

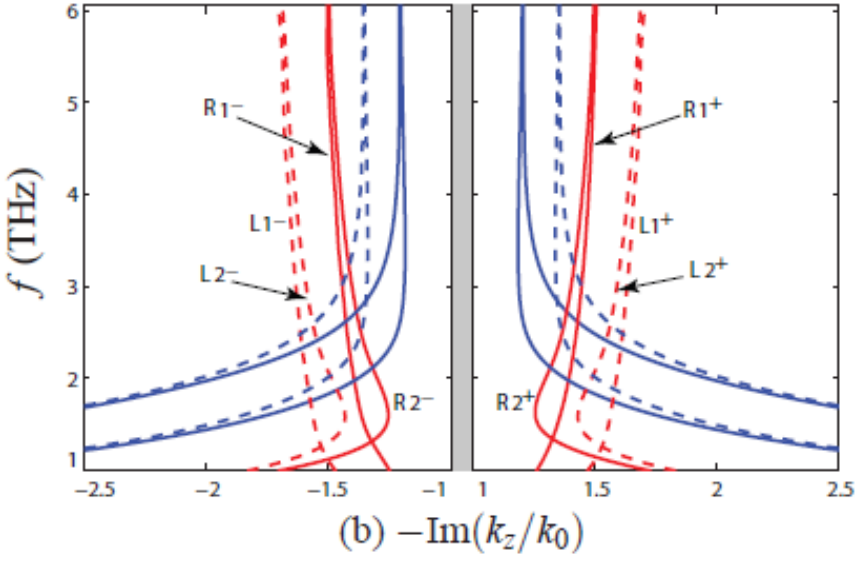
- I. Nonreciprocal Phase Shifter
- **II. Non-reciprocal Coupler**
- III. Magnetoplasmonic Isolators
- IV. Magnetic Sensor

❖ Conclusions & Questions

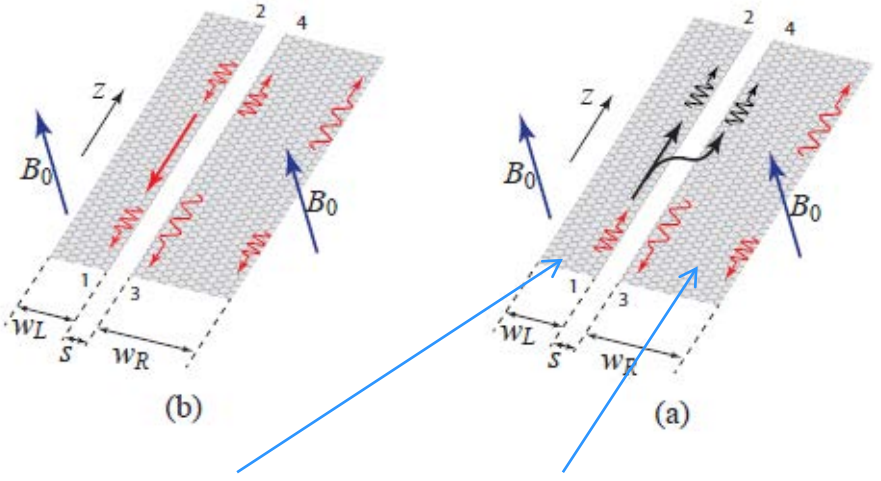
Nonreciprocal Magnetoplasmon Coupler



(a) $\mathrm{Re}(k_z/k_0)$

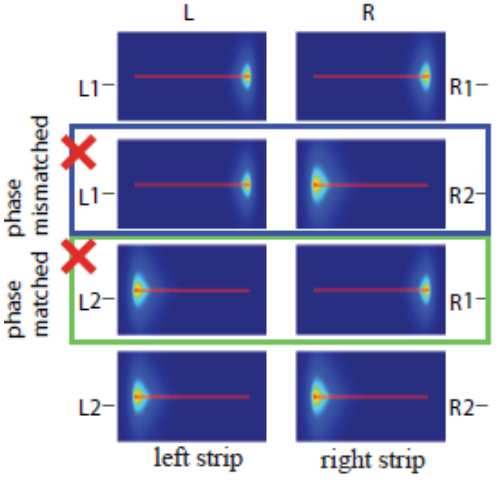


(b) $-\mathrm{Im}(k_z/k_0)$

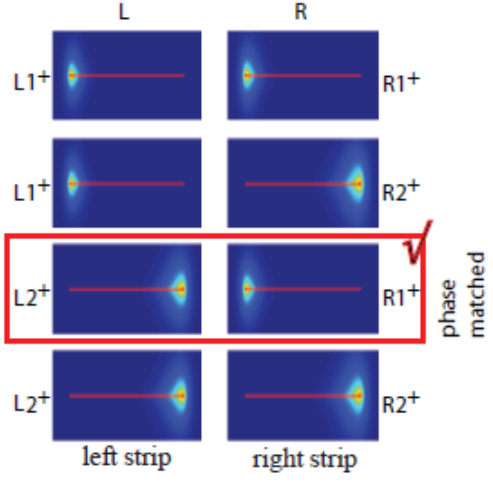


left strip:
$n_s = 8 \times 10^{12}$ cm^{-2}
$\tau = 0.1$ ps
$w = 100$ μm
$B = 1$ T

right strip:
$n_s = 10^{13}$ cm^{-2}
$\tau = 0.1$ ps
$w = 100$ μm
$B = 1$ T

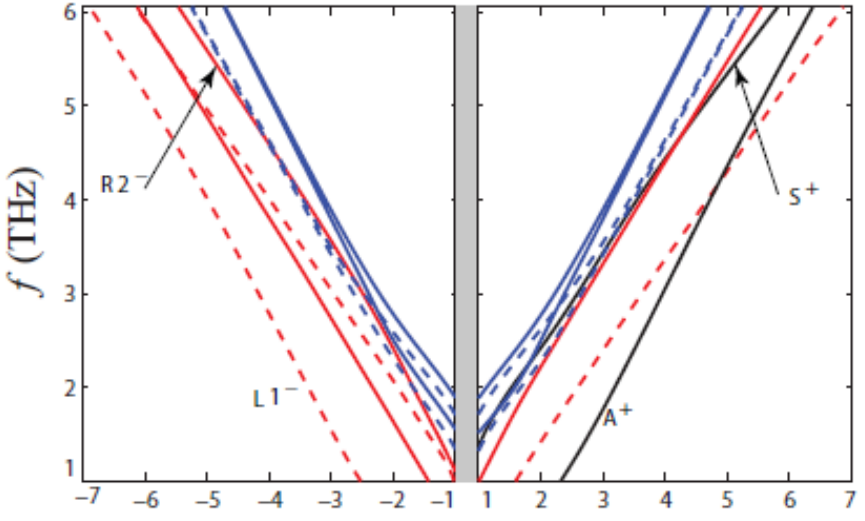


backward ($-z$)

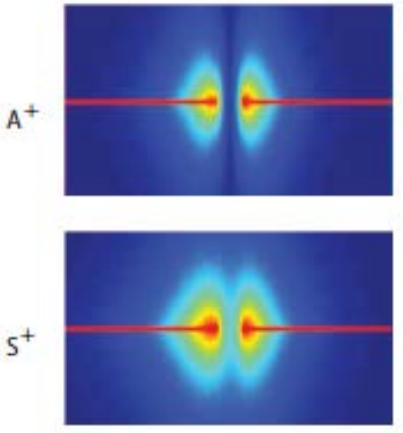


forward ($+z$)

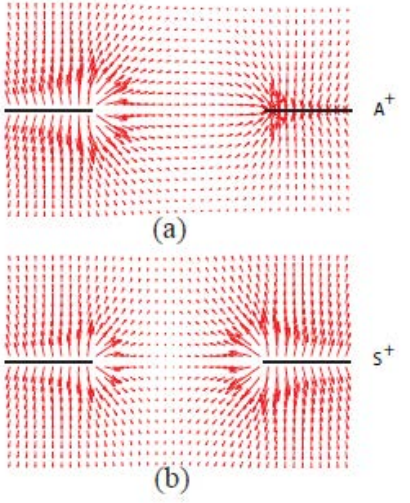
Nonreciprocal Magnetoplasmon Coupler

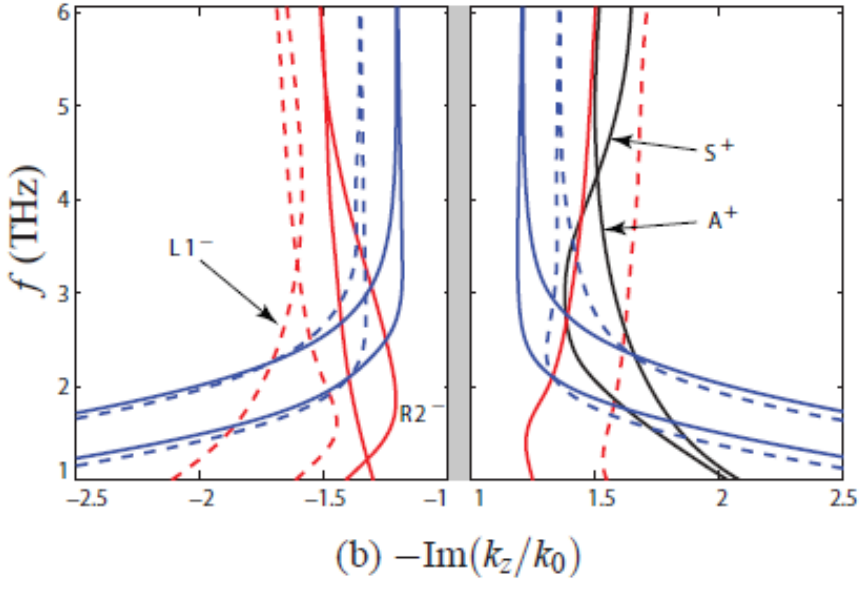


(a) $\mathrm{Re}(k_z/k_0)$

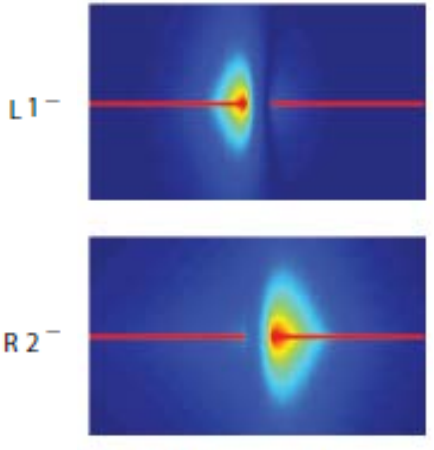


(a) forward $(+z)$

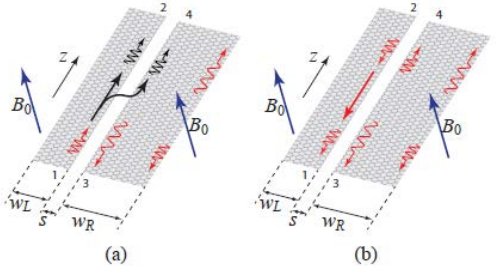




(b) $-\mathrm{Im}(k_z/k_0)$



(b) backward $(-z)$



Outline

I. Introduction to graphene magnetoplasmons

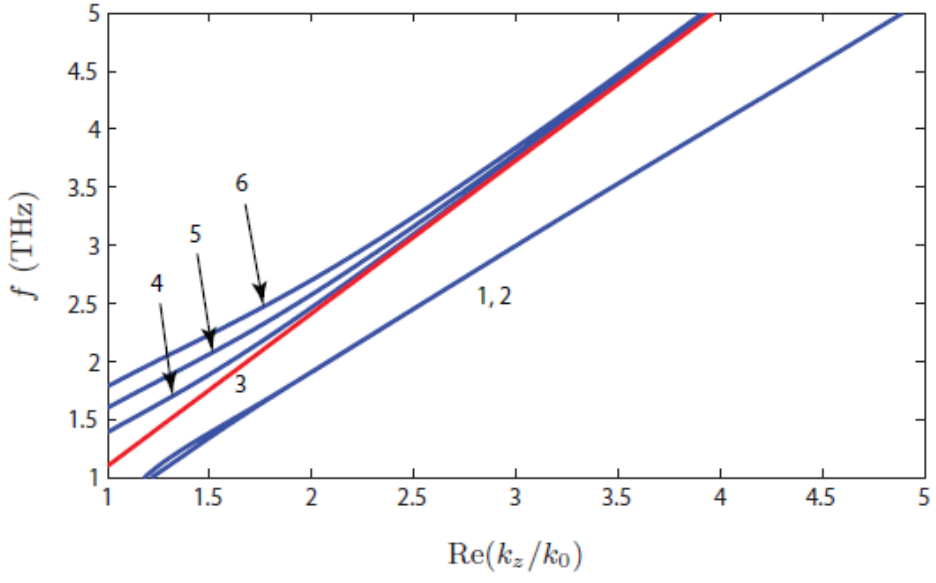
II. Principles of Non-reciprocity

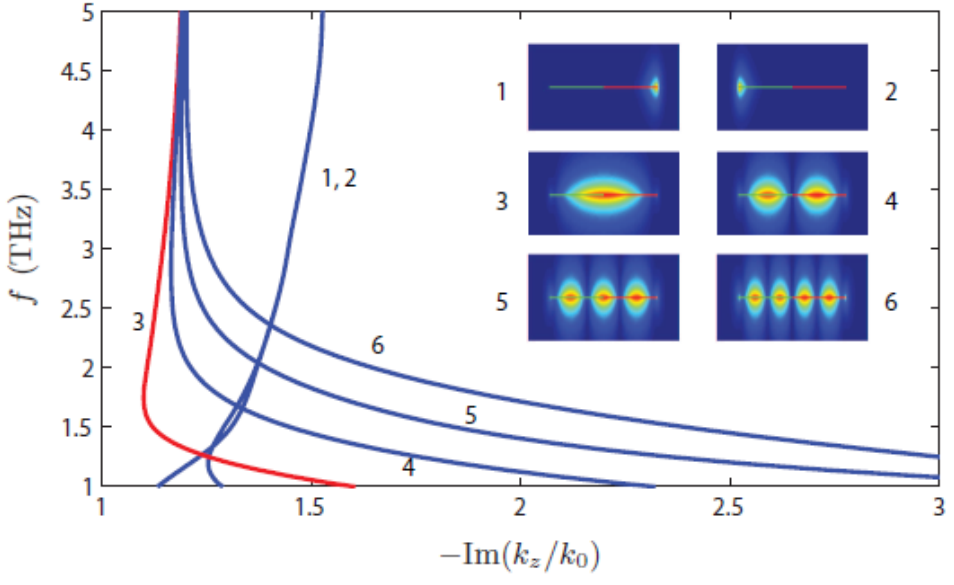
III. Structures and Devices

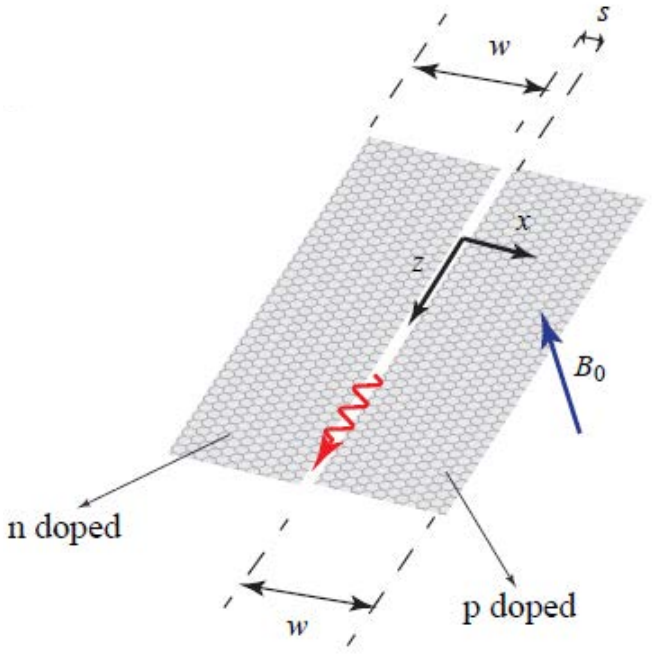
- I. Nonreciprocal Phase Shifter
- II. Non-reciprocal Coupler
- **III. Magnetoplasmonic Isolators (Chemical Doping)**
- IV. Magnetic Sensor

❖ Conclusions & Questions

Graphene Plasmonic Isolator



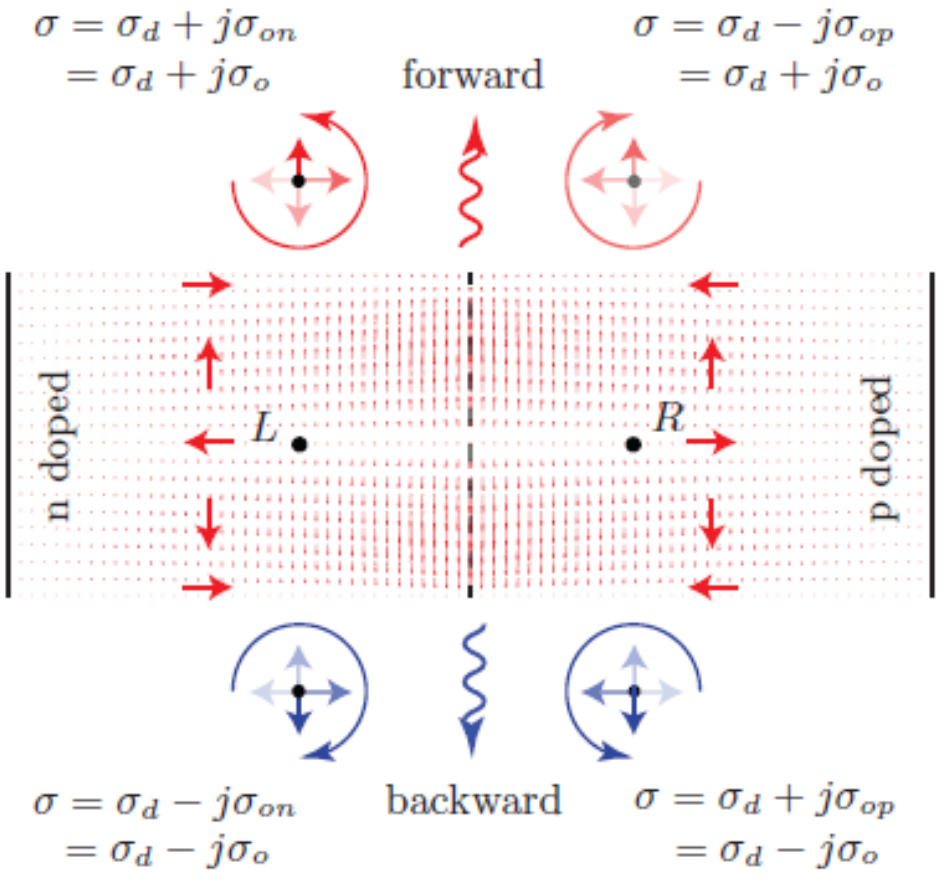


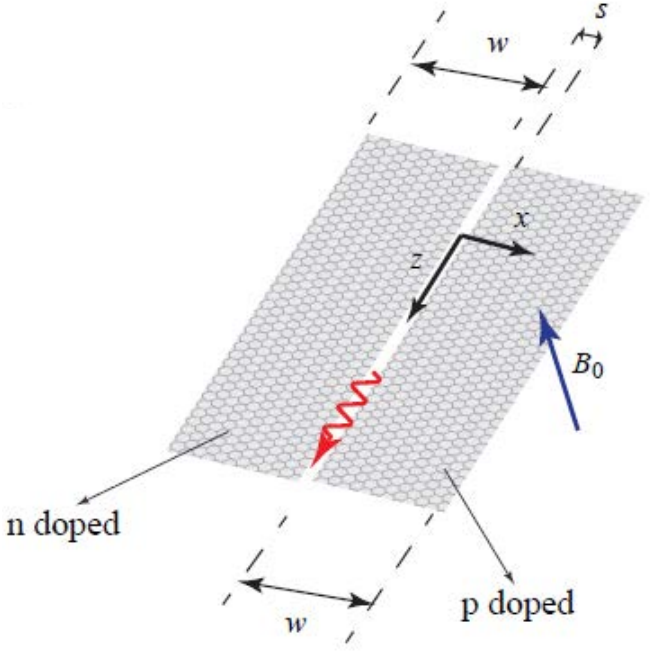


no magnetic bias:
- symmetric dispersion for opposite directions

N. Chamanara, D. L. Sounas, T. Szkopek, and C. Caloz, *Opt. express., vol. 21, no. 21, pp. 25356–25363, 2013.*

P-N Junction Mode Forward Vs. Backward





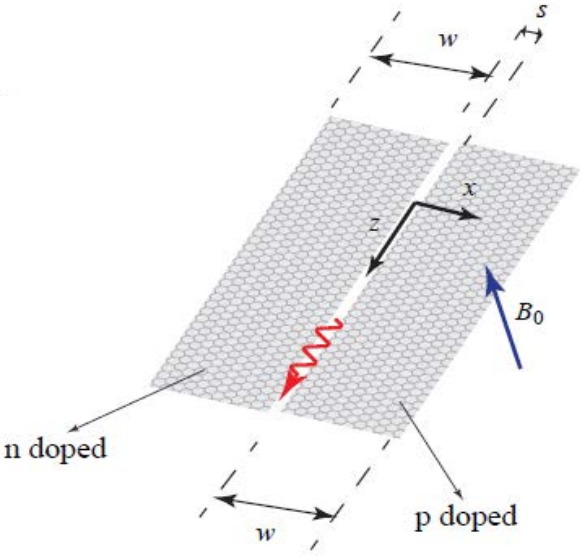
$B \uparrow$ →

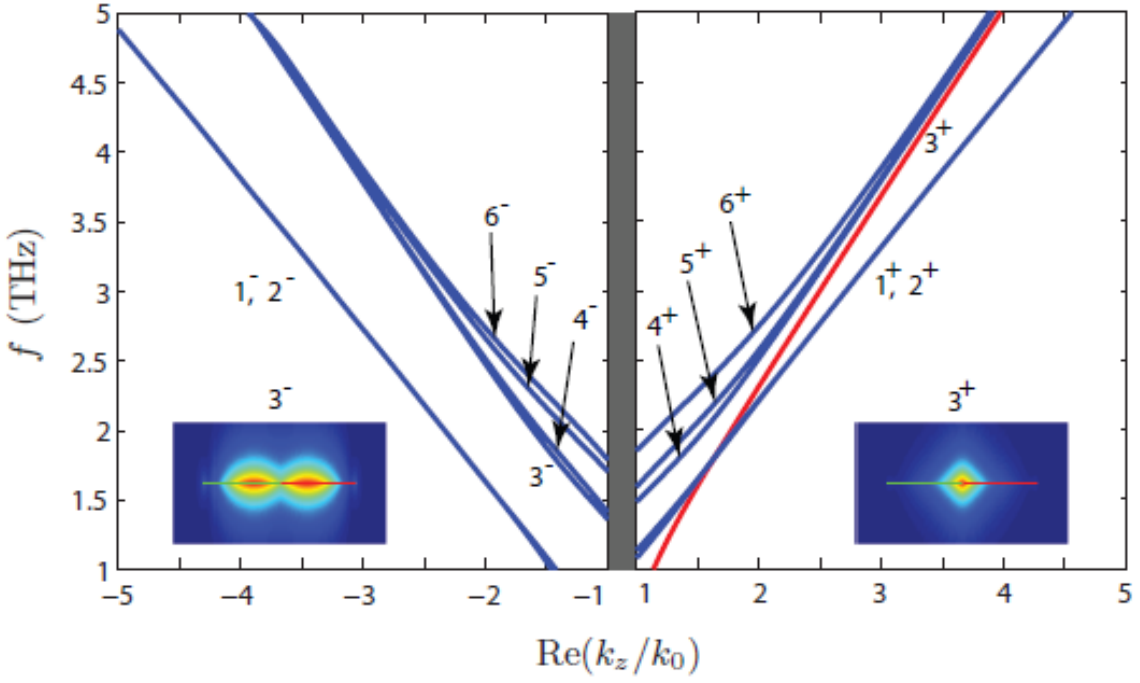
n-doped: $\bar{\bar{\sigma}} = \sigma_d(\hat{\mathbf{x}}\hat{\mathbf{x}} + \hat{\mathbf{z}}\hat{\mathbf{z}}) + \sigma_o(\hat{\mathbf{x}}\hat{\mathbf{z}} - \hat{\mathbf{z}}\hat{\mathbf{x}})$

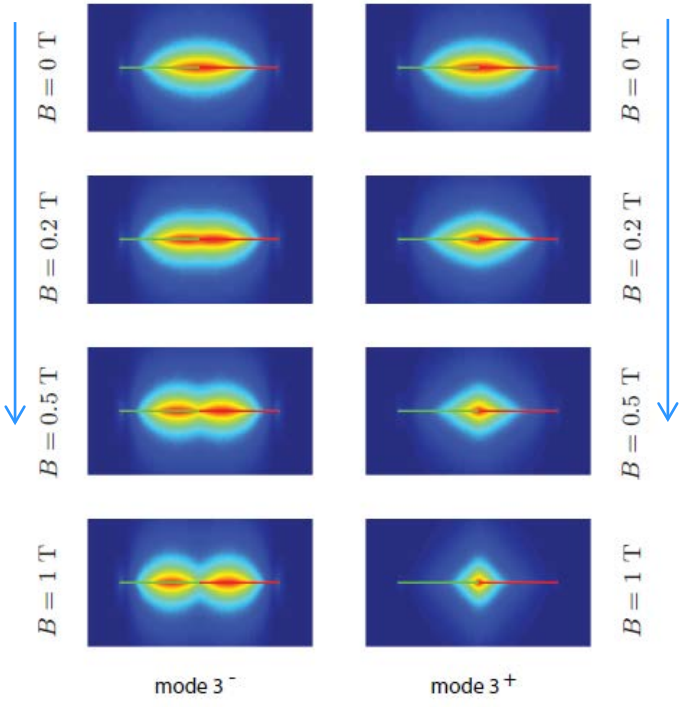
p-doped: $\bar{\bar{\sigma}} = \sigma_d(\hat{\mathbf{x}}\hat{\mathbf{x}} + \hat{\mathbf{z}}\hat{\mathbf{z}}) - \sigma_o(\hat{\mathbf{x}}\hat{\mathbf{z}} - \hat{\mathbf{z}}\hat{\mathbf{x}})$

Graphene Magnetoplasmon Isolator

with magnetic bias:
- unsymmetric dispersion for opposite directions
- mode 3 is localized at the p-n junction only
in the forward direction







Outline

I. Introduction to graphene magnetoplasmons

II. Principles of Non-reciprocity

III. Structures and Devices

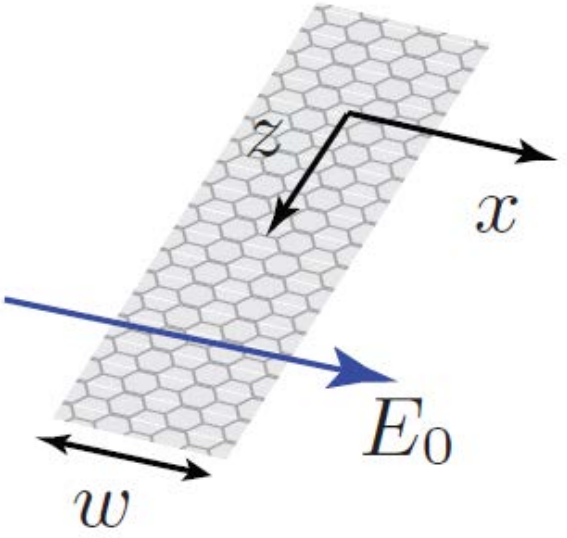
- I. Nonreciprocal Phase Shifter
- II. Non-reciprocal Coupler
- **III. Magnetoplasmonic Isolators (Electrical Doping)**
- IV. Magnetic Sensor

❖ Conclusions & Questions

Electrically Doped Graphene PN Junction

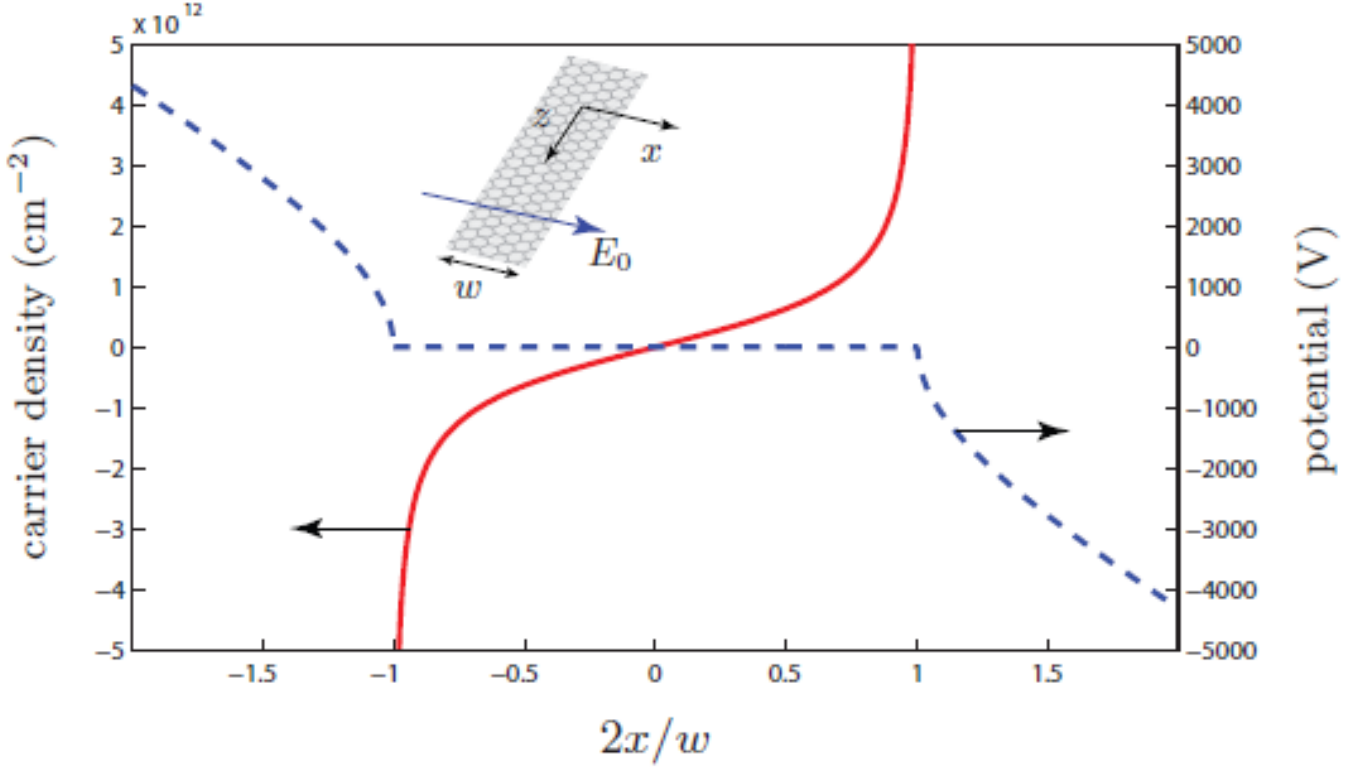
$$\int_{-w/2}^{w/2} \rho(x',y')G(x,y;x',y')dx' - E_0 x = 0, \qquad (1a)$$

$$-w/2 \le x \le w/2, \quad y = 0, \quad y' = 0, \qquad (1b)$$



2D Green function for Poisson equation

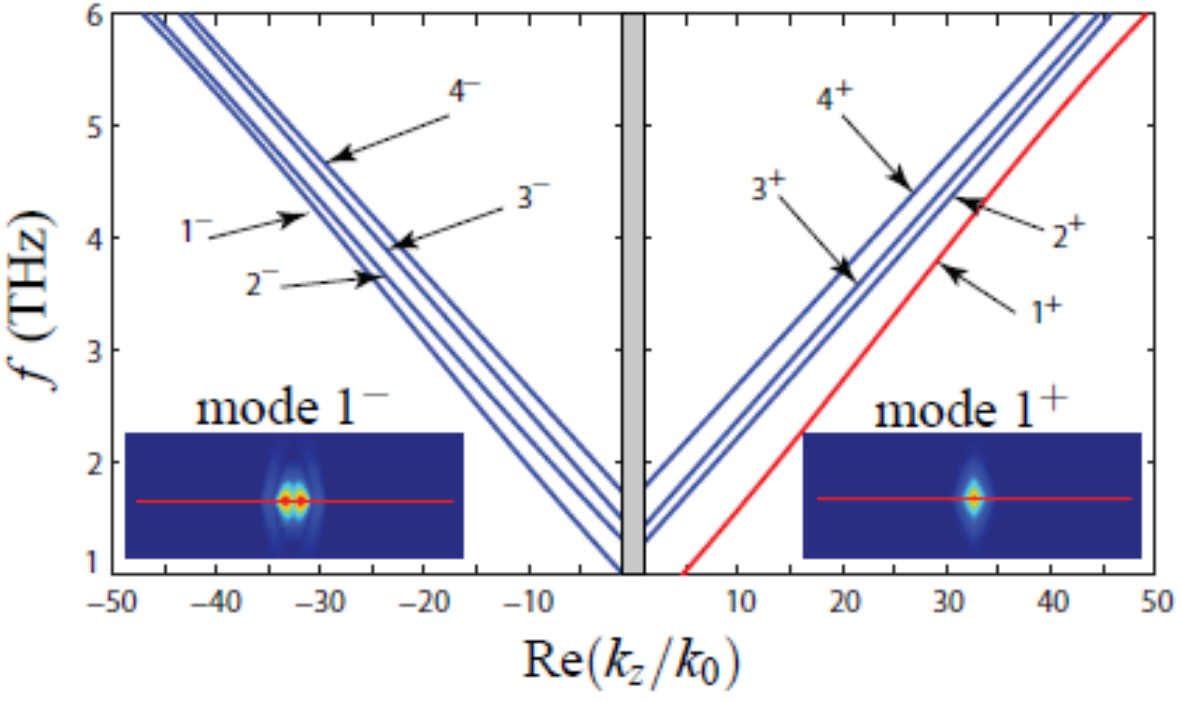
$$G(x,y;x',y') = \frac{-1}{2\pi\epsilon_0} \ln \sqrt{(x'-x)^2 + (y'-y)^2}$$

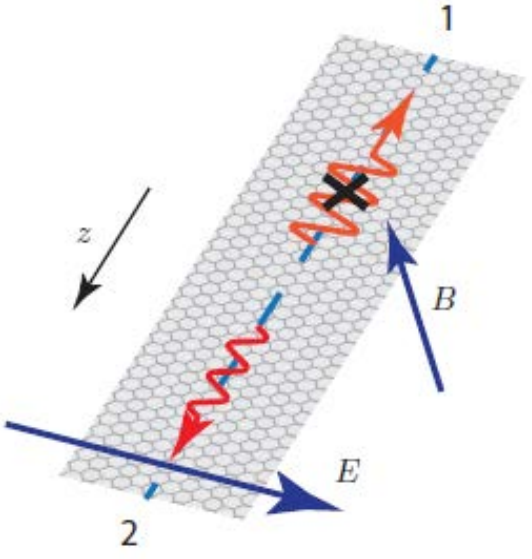


$w = 50\ \mu\text{m}$

$E_0 = 10^8\ \text{V/m}$

Electrically Doped Plasmonic ISolator





electrically doped plasmonic isolator

$B \uparrow \quad \Rightarrow \quad$ the localized p-n junction mode propagates only in the forward direction

$w = 50\ \mu\text{m}$
$E_0 = 10^8\ \text{V/m}$
$B = 0.1\ \text{T}$

Outline

I. Introduction to graphene magnetoplasmons

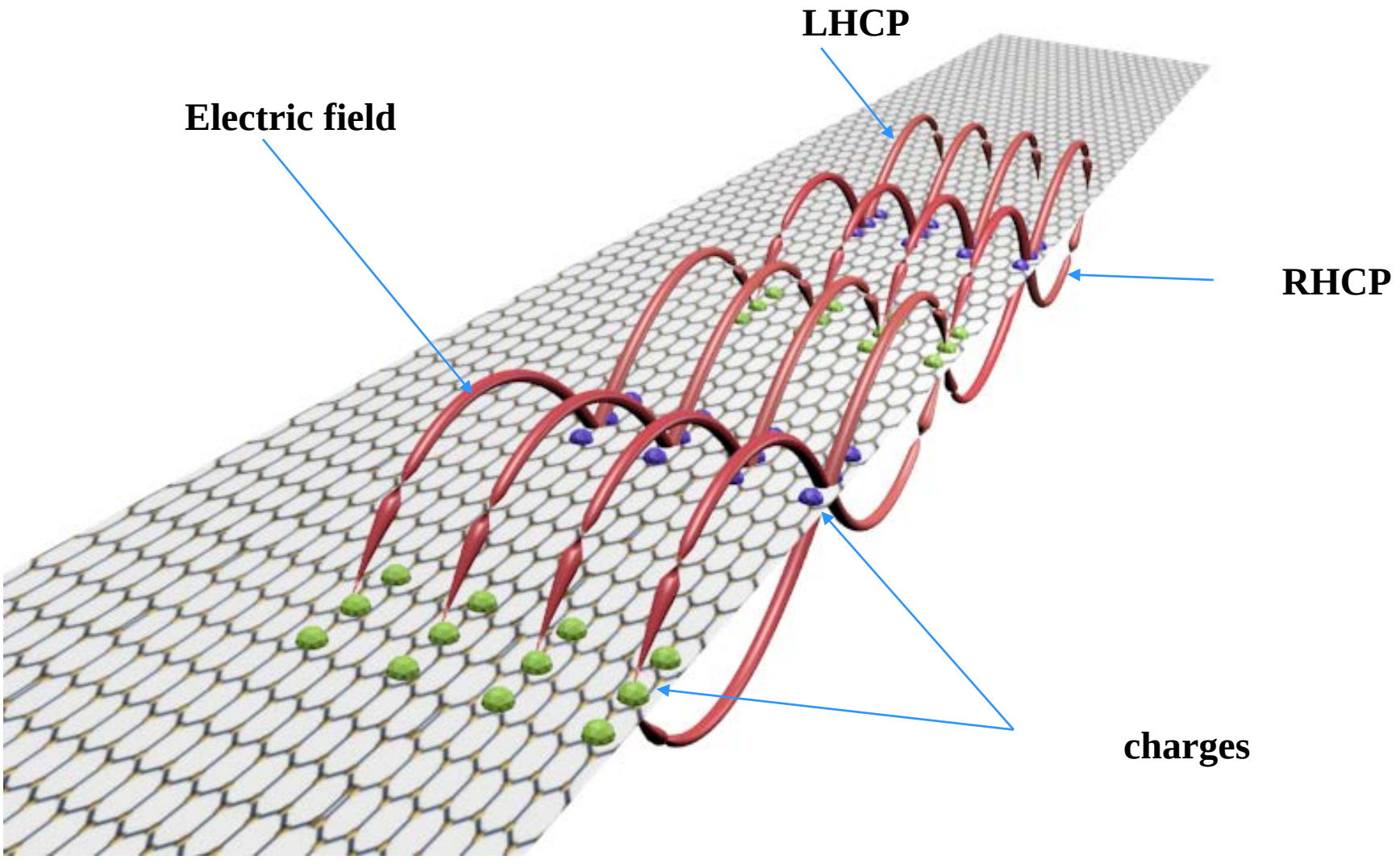
II. Principles of Non-reciprocity

III. Structures and Devices

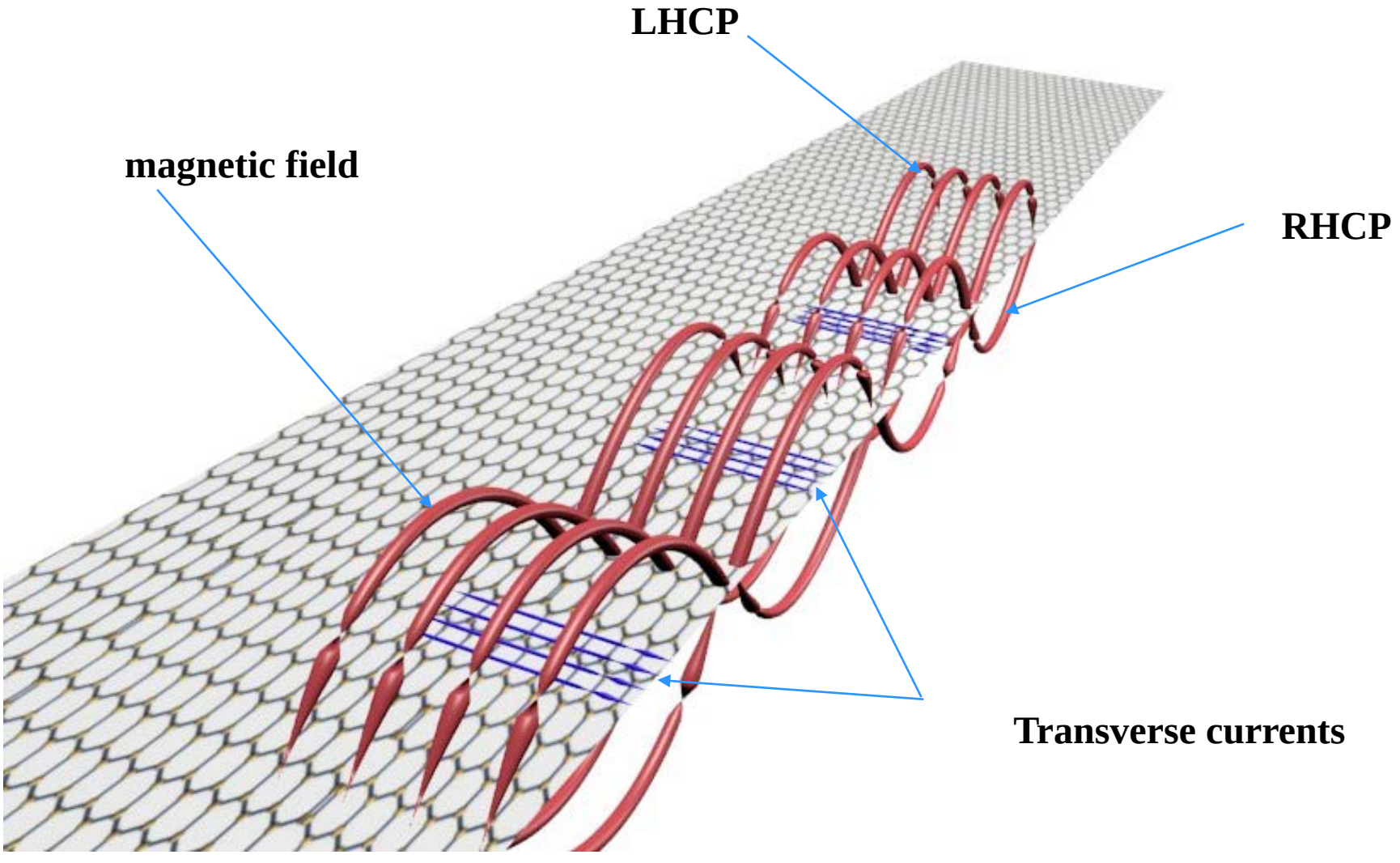
- I. Nonreciprocal Phase Shifter
- II. Non-reciprocal Coupler
- **III. Magnetoplasmonic Isolators (Graphene on Ferrite Substrate)**
- IV. Magnetic Sensor

❖ Conclusions & Questions

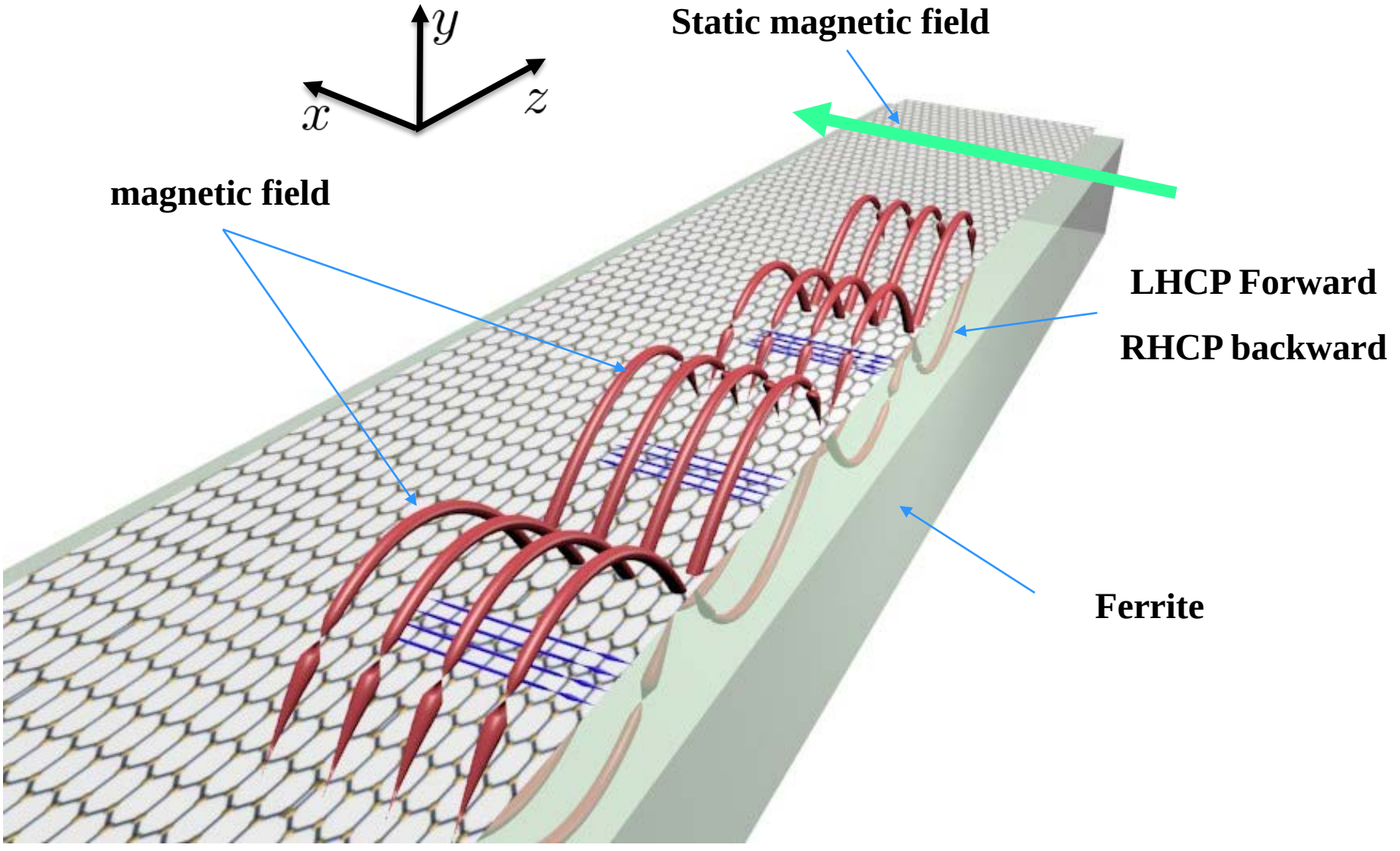
TM (conventional) Surface Plasmons



Graphene TE Surface Plasmons



TE Plasmons Interaction with Ferrite Substrate



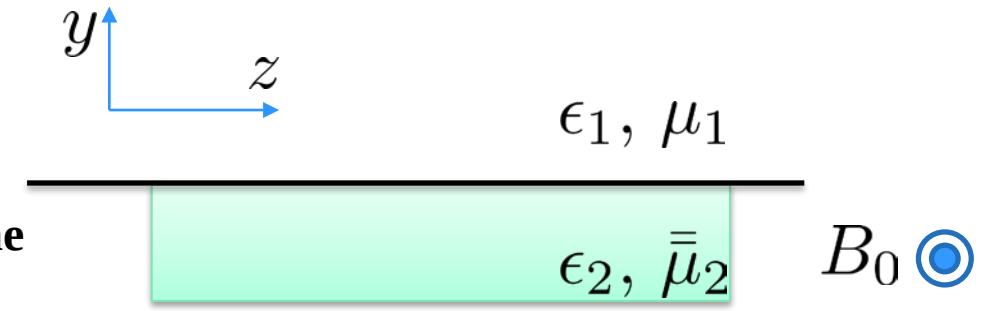
Analysis 1

Electric fields

$$\mathbf{E}_1 = \left(E_{x1}, E_{y1}, E_{z1}\right) e^{-\alpha_1 y - ikz}$$

$$\mathbf{E}_2 = \left(E_{x2}, E_{y2}, E_{z2}\right) e^{+\alpha_2 y - ikz}$$

Graphene sheet



Ferrite

$$\mu_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \mu_{rd2} & -\mu_{ro2} \\ 0 & \mu_{ro2} & \mu_{rd2} \end{bmatrix}$$

Magnetic fields

$$\mathbf{H} = \frac{-1}{i\omega\mu_0} \bar{\bar{\boldsymbol{\mu}}}_r^{-1} \cdot \nabla \times \mathbf{E}$$

$$H_1 = \begin{bmatrix} \dfrac{i}{\mu_0\mu_{r1}\omega}\left(iE_{y1}ke^{-\alpha_1 y - ikz} - E_{z1}\alpha_1 e^{-\alpha_1 y - ikz}\right) \\ \dfrac{E_{x1}k}{\mu_0\mu_{r1}\omega} e^{-\alpha_1 y - ikz} \\ \dfrac{iE_{x1}\alpha_1}{\mu_0\mu_{r1}\omega} e^{-\alpha_1 y - ikz} \end{bmatrix}$$

$$H_2 = \begin{bmatrix} \dfrac{i}{\mu_0\omega}\left(iE_{y2}ke^{\alpha_2 y - ikz} + E_{z2}\alpha_2 e^{\alpha_2 y - ikz}\right) \\ -\dfrac{iE_{x2}\alpha_2\mu_{ro2}e^{\alpha_2 y - ikz}}{\mu_0\mu_{rd2}\omega\left(\mu_{rd2} + \frac{\mu_{ro2}^2}{\mu_{rd2}}\right)} + \dfrac{E_{x2}k}{\mu_0\omega}\left(\dfrac{1}{\mu_{rd2}} - \dfrac{\mu_{ro2}^2}{\mu_{rd2}^2\left(\mu_{rd2} + \frac{\mu_{ro2}^2}{\mu_{rd2}}\right)}\right) e^{\alpha_2 y - ikz} \\ -\dfrac{iE_{x2}\alpha_2 e^{\alpha_2 y - ikz}}{\mu_0\omega\left(\mu_{rd2} + \frac{\mu_{ro2}^2}{\mu_{rd2}}\right)} - \dfrac{E_{x2}\mu_{ro2}ke^{\alpha_2 y - ikz}}{\mu_0\mu_{rd2}\omega\left(\mu_{rd2} + \frac{\mu_{ro2}^2}{\mu_{rd2}}\right)} \end{bmatrix}$$

Analysis 2

Boundary condition:

$$\mathbf{a}_y \times \left(\mathbf{H}_1 - \mathbf{H}_2\right) = \sigma \mathbf{E}_\mathbf{T}$$

$$\begin{bmatrix} \frac{1}{\mu_0\mu_{r1}\omega\left(\mu_{rd2}^2+\mu_{ro2}^2\right)}\left(iE_{x1}\alpha_1\left(\mu_{rd2}^2+\mu_{ro2}^2\right)-E_{x1}\mu_0\mu_{r1}\omega\sigma\left(\mu_{rd2}^2+\mu_{ro2}^2\right)+E_{x2}\mu_{r1}\left(i\alpha_2\mu_{rd2}+\mu_{ro2}k\right)\right) \\ 0 \\ \frac{1}{\mu_0\mu_{r1}\omega}\left(E_{y1}k-E_{y2}\mu_{r1}k+iE_{z1}\alpha_1-E_{z1}\mu_0\mu_{r1}\omega\sigma+iE_{z2}\alpha_2\mu_{r1}\right) \end{bmatrix} = \mathbf{0} \quad \textbf{(1)}$$

Normal components: $\nabla \cdot \mathbf{E} = 0$

$$E_{y1} = -\frac{iE_{z1}}{\alpha_1}k \qquad E_{y2} = \frac{iE_{z2}}{\alpha_2}k$$

Substituting into (1)

$$\begin{bmatrix} 0 & B_{12} \\ B_{21} & 0 \end{bmatrix}\begin{pmatrix} E_{x1} \\ E_{z1} \end{pmatrix} = 0$$

$$B_{12} = \frac{1}{\mu_0\mu_{r1}\omega\left(\mu_{rd2}^2+\mu_{ro2}^2\right)}\left(i\alpha_1\left(\mu_{rd2}^2+\mu_{ro2}^2\right)-\mu_0\mu_{r1}\omega\sigma\left(\mu_{rd2}^2+\mu_{ro2}^2\right)+\mu_{r1}\left(i\alpha_2\mu_{rd2}+\mu_{ro2}k\right)\right)$$

$$B_{21} = \frac{i\alpha_1}{\mu_0\mu_{r1}\omega}+\frac{i\alpha_2}{\mu_0\omega}-\sigma-\frac{ik^2}{\alpha_2\mu_0\omega}-\frac{ik^2}{\alpha_1\mu_0\mu_{r1}\omega}$$

Analysis 3

$$\begin{bmatrix} 0 & B_{12} \\ B_{21} & 0 \end{bmatrix} \begin{pmatrix} E_{x1} \\ E_{z1} \end{pmatrix} = 0$$

Eigenvalues & eigenvectors

$B_{21}(k) = 0, \quad \begin{pmatrix} 0 \\ E_{z1} \end{pmatrix}$ **TM , reciprocal**

$B_{12}(k) = 0, \quad \begin{pmatrix} E_{x1} \\ 0 \end{pmatrix}$ **TE , nonreciprocal**

$$B_{12}(k) = \frac{1}{\mu_0 \mu_{r1} \omega \left(\mu_{rd2}^2 + \mu_{ro2}^2\right)} \left(i\alpha_1 \left(\mu_{rd2}^2 + \mu_{ro2}^2\right) - \mu_0 \mu_{r1} \omega \sigma \left(\mu_{rd2}^2 + \mu_{ro2}^2\right) + \mu_{r1} \left(i\alpha_2 \mu_{rd2} + \mu_{ro2} k\right)\right) = 0$$

Getting $\alpha_1(k)$ and $\alpha_2(k)$: $\nabla \times \left(\bar{\bar{\mu}}_r^{-1} \nabla \times \mathbf{E}\right) - \omega^2 \mu_0 \varepsilon_0 \varepsilon_r \mathbf{E} = 0, \qquad \nabla \cdot \mathbf{E} = 0$

Region (1)

$$\begin{bmatrix} E_{x1}\left(-\alpha_1^2 - \epsilon_0 \epsilon_{r1} \mu_0 \mu_{r1} \omega^2 + k^2\right) \\ \frac{iE_{z1}}{\alpha_1} k\left(\alpha_1^2 + \epsilon_0 \epsilon_{r1} \mu_0 \mu_{r1} \omega^2 - k^2\right) \\ E_{z1}\left(-\alpha_1^2 - \epsilon_0 \epsilon_{r1} \mu_0 \mu_{r1} \omega^2 + k^2\right) \end{bmatrix} = 0$$

Region (2)

$$\begin{bmatrix} \frac{E_{x2}}{\mu_{rd2}^2 + \mu_{ro2}^2}\left(-\alpha_2^2 \mu_{rd2} - \epsilon_0 \epsilon_{r2} \mu_0 \mu_{rd2}^2 \omega^2 - \epsilon_0 \epsilon_{r2} \mu_0 \mu_{ro2}^2 \omega^2 + \mu_{rd2} k^2\right) \\ \frac{iE_{z2}}{\alpha_2} k\left(-\alpha_2^2 - \epsilon_0 \epsilon_{r2} \mu_0 \omega^2 + k^2\right) \\ E_{z2}\left(-\alpha_2^2 - \epsilon_0 \epsilon_{r2} \mu_0 \omega^2 + k^2\right) \end{bmatrix} = 0$$

Analysis 4

$$\alpha_1 = \sqrt{-\epsilon_0 \epsilon_{r1} \mu_0 \mu_{r1} \omega^2 + k^2}$$

$$\alpha_2 = \sqrt{-\epsilon_0 \epsilon_{r2} \mu_0 \mu_{rd2} \omega^2 - \frac{\epsilon_0 \epsilon_{r2}}{\mu_{rd2}} \mu_0 \mu_{ro2}^2 \omega^2 + k^2}$$

Dispersion equation:

$$\left(-\mu_0 \mu_{r1} \omega \sigma \left(\mu_{rd2}^2 + \mu_{ro2}^2\right) + \mu_{r1} \left(i \mu_{rd2} \sqrt{\frac{1}{\mu_{rd2}} \left(-\epsilon_0 \epsilon_{r2} \mu_0 \mu_{ro2}^2 \omega^2 + \mu_{rd2} \left(-\epsilon_0 \epsilon_{r2} \mu_0 \mu_{rd2} \omega^2 + k^2\right)\right)} + \mu_{ro2} k\right) + i \left(\mu_{rd2}^2 + \mu_{ro2}^2\right) \sqrt{-\epsilon_0 \epsilon_{r1} \mu_0 \mu_{r1} \omega^2 + k^2}\right)$$

$= 0$

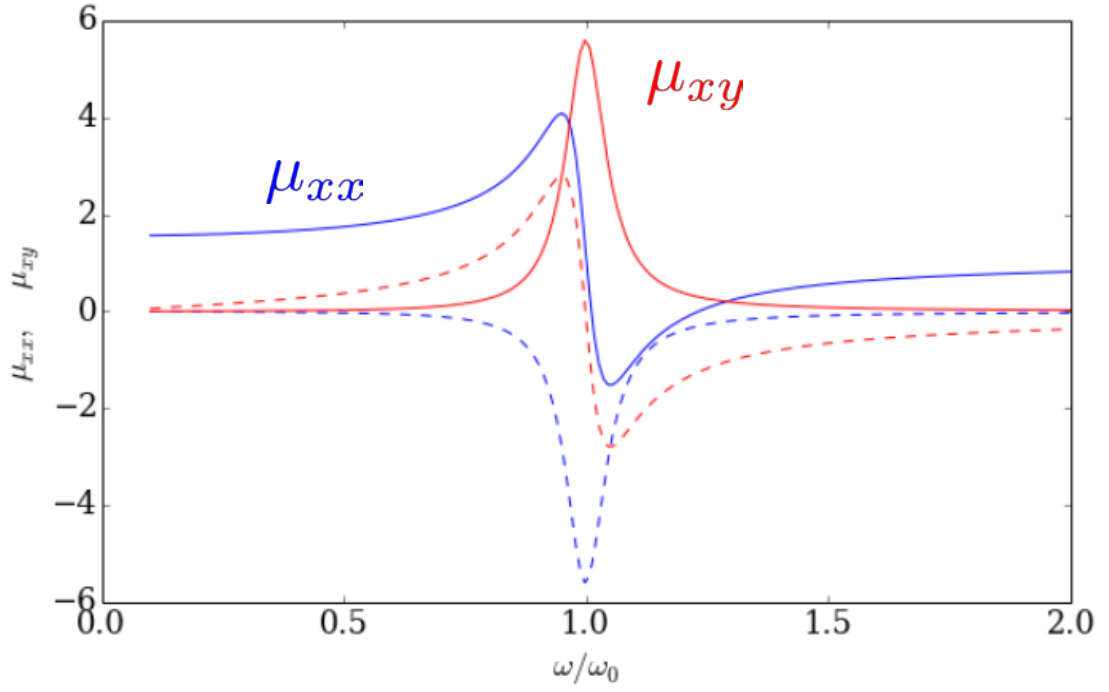
indicating nonreciprocity

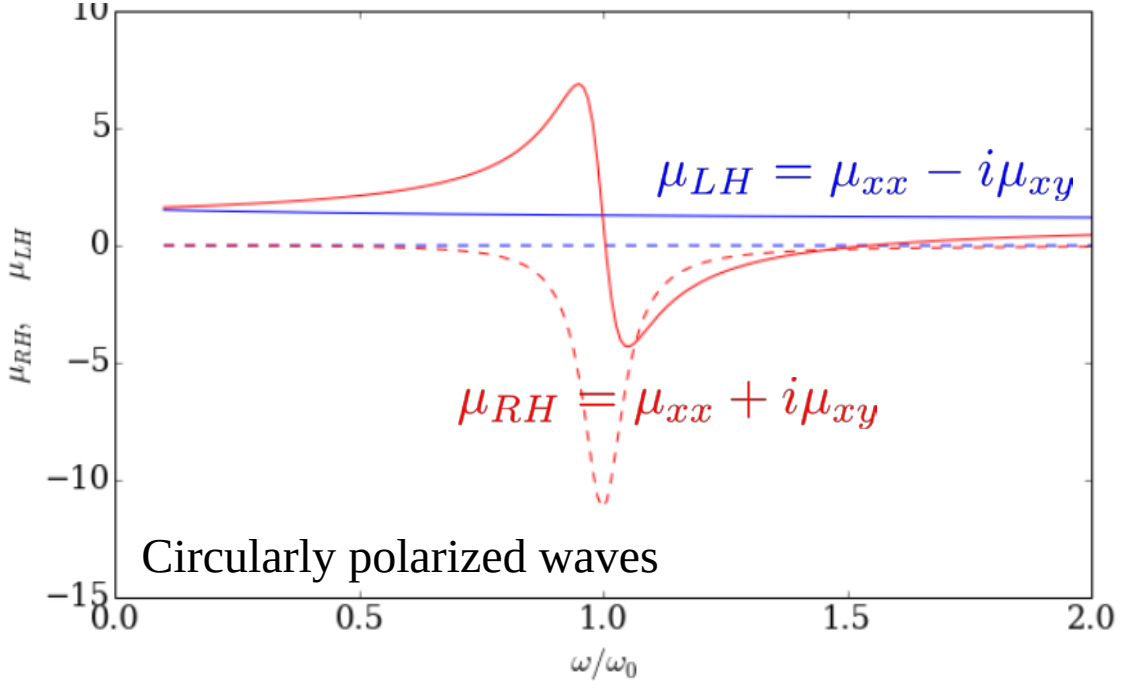
Results - Ferrite Substrate Permeability Tensor

ferrite parameters:

$$f_0 = 50GHz$$
$$f_m = 10.6GHz$$
$$\alpha = 0.05$$

$$B_0 = 1.8\ \mathrm{T}$$
$$\mu_0 M_s = 0.38\ \mathrm{T}$$

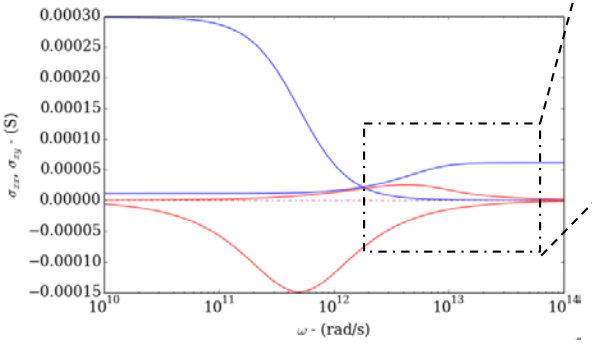


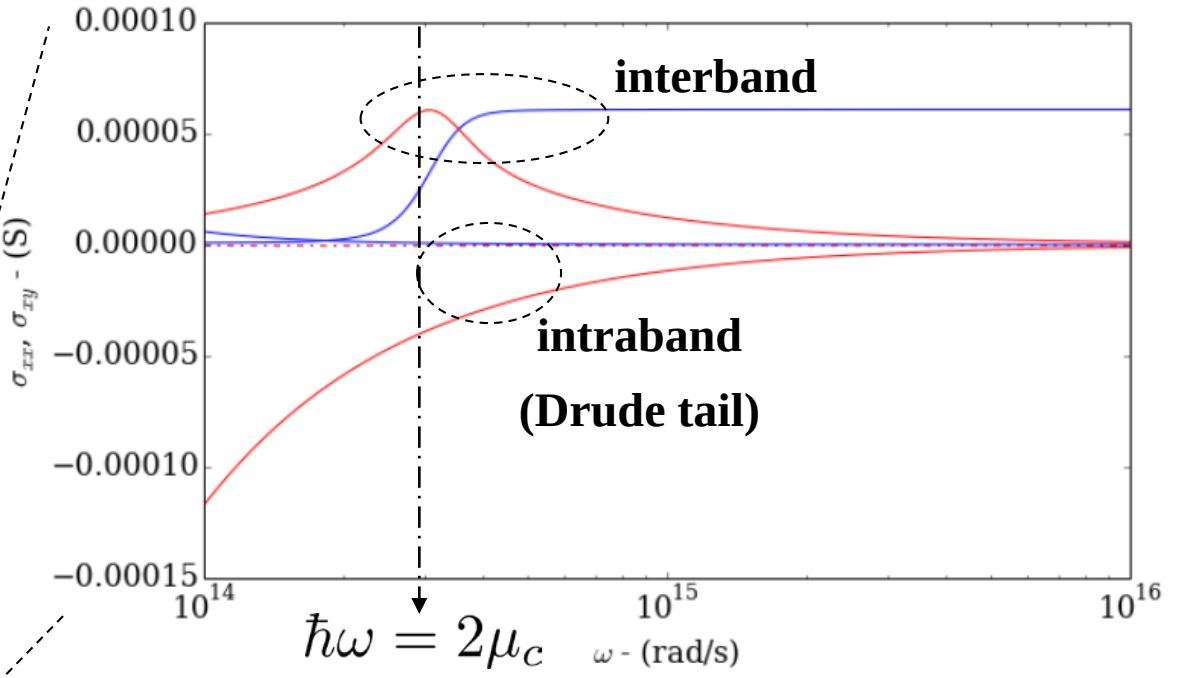


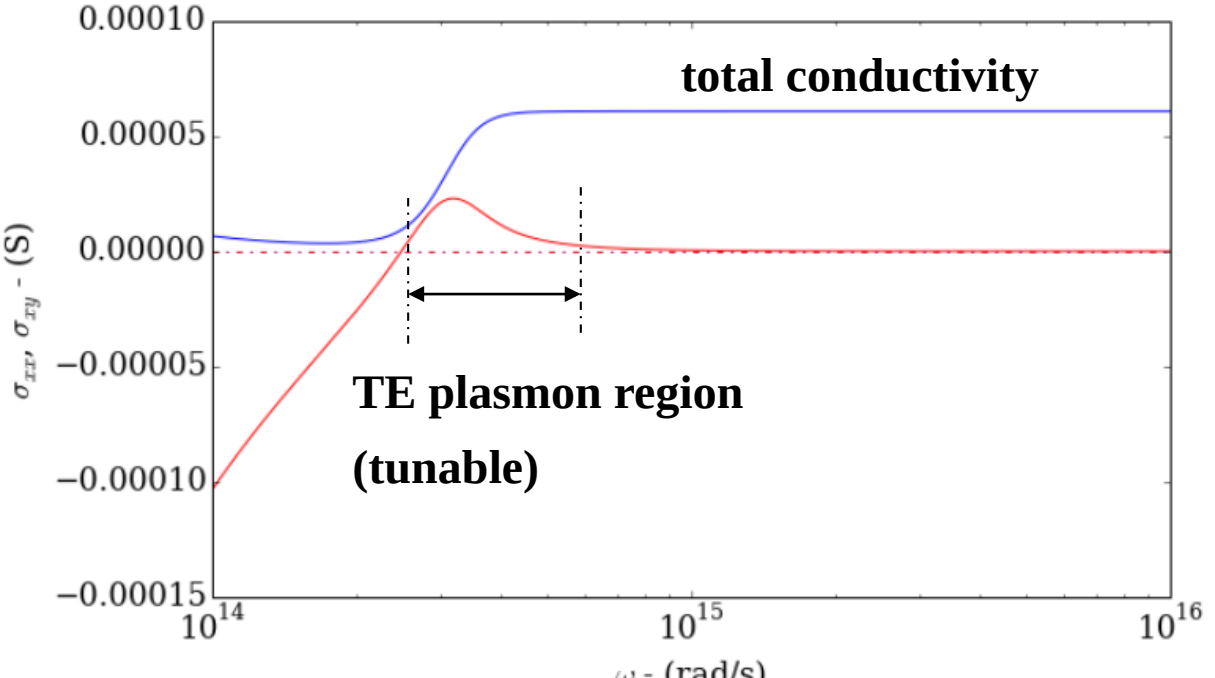
Graphene Intraband and interband conductivities

graphene parameters:

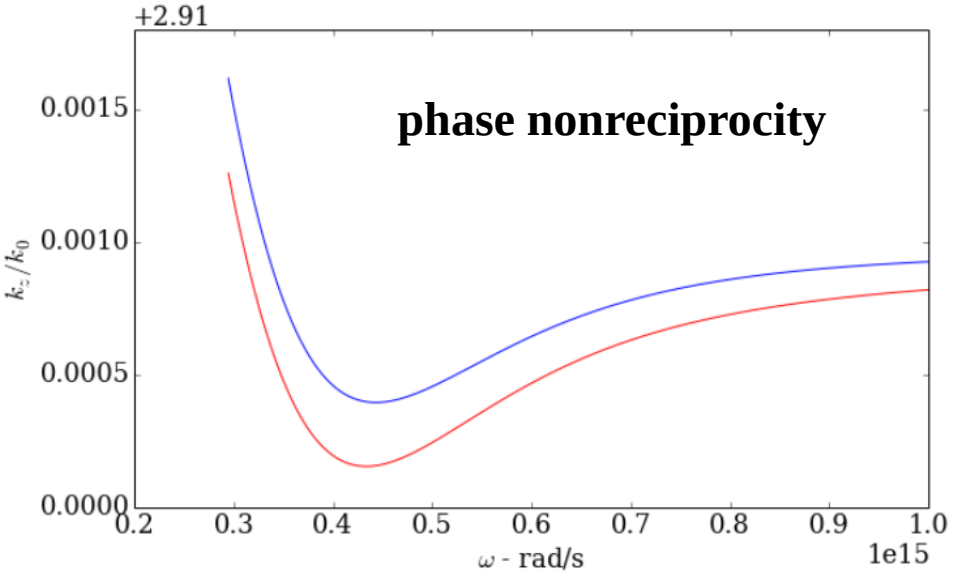
$$\mu_c = 0.1 \text{ eV}$$
$$\tau = 0.2 \text{ ps}$$
$$\text{T} = 300 \text{ K}$$

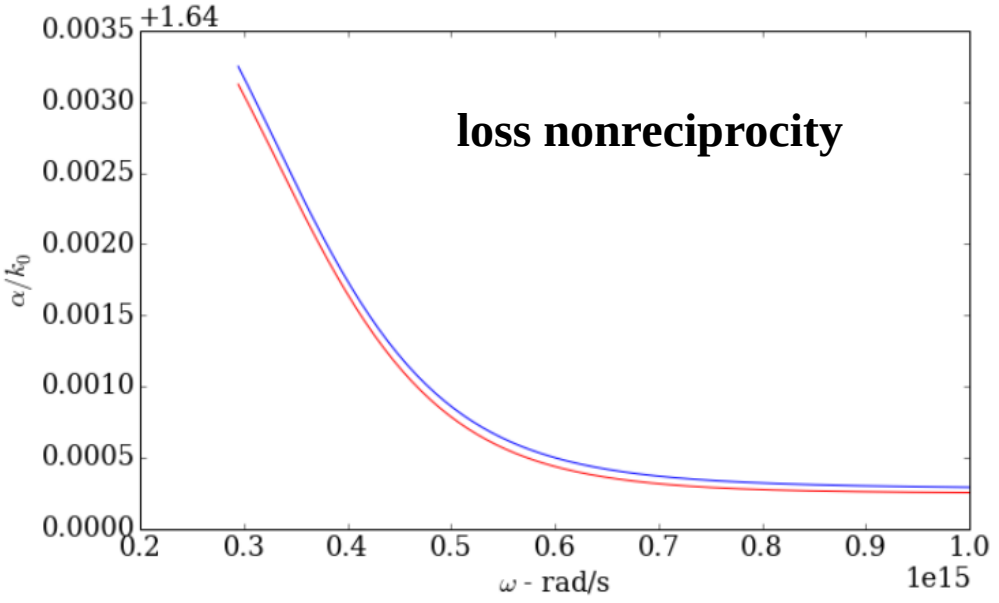






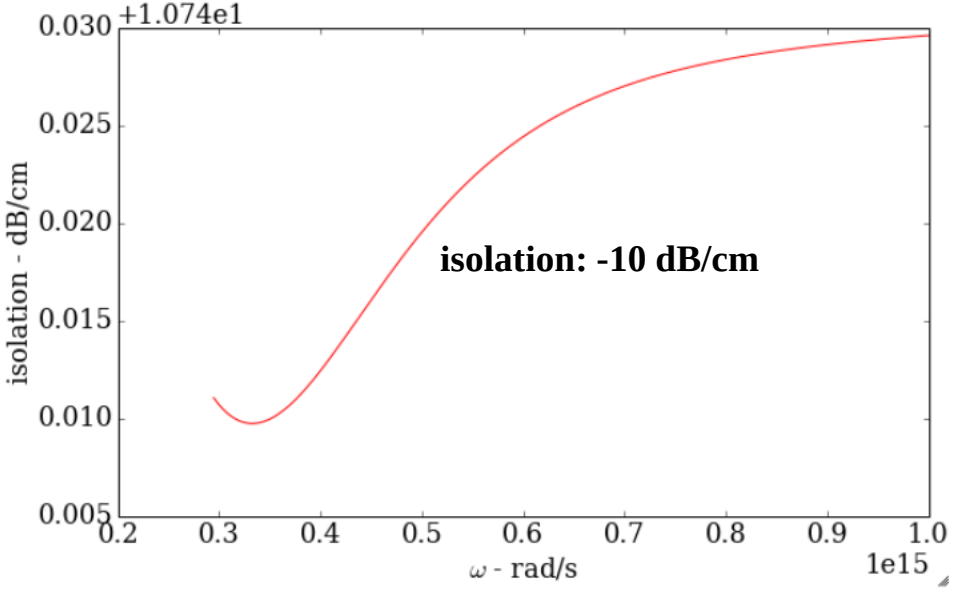
Dispersion Curves – Isolation Result



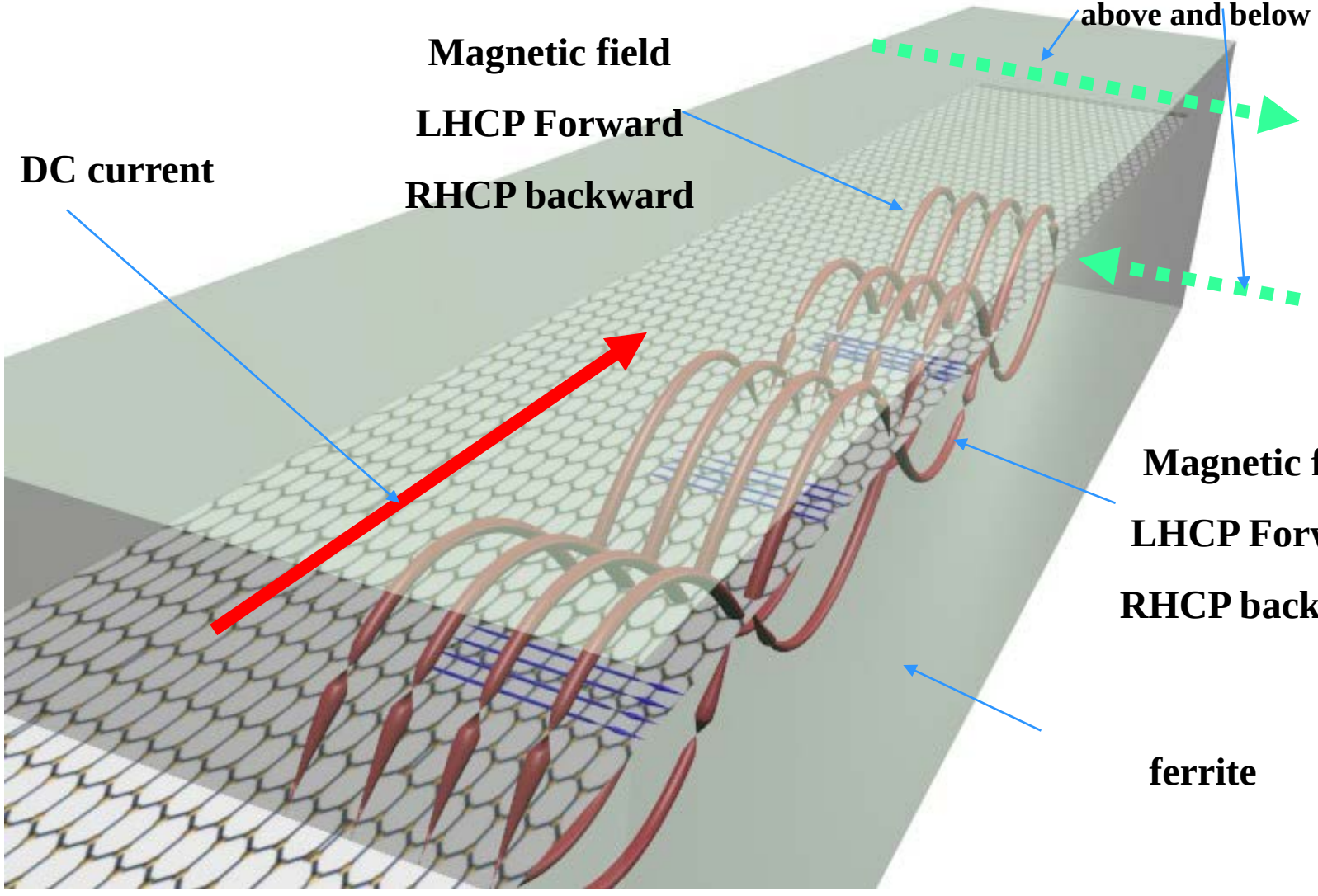


substrate parameters:

$$\epsilon_{r1} = 1,\ \mu_{r1} = 1$$
$$\epsilon_{r2} = 9$$



DC-Current-Based Graphene Plasmonic Isolator



Outline

I. Introduction to graphene magnetoplasmons

II. Principles of Non-reciprocity

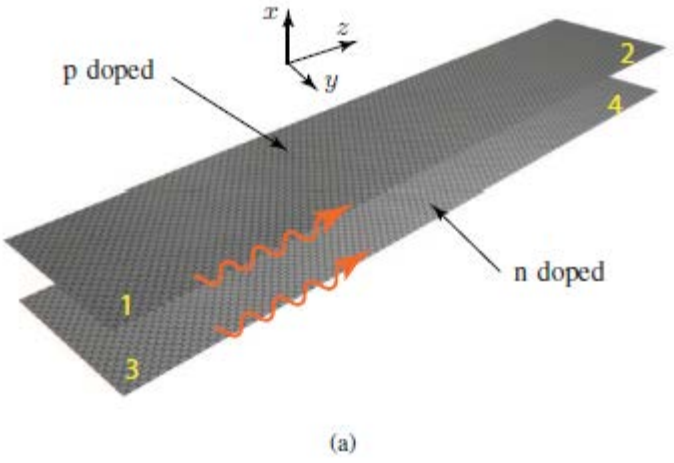
III. Structures and Devices

- I. Nonreciprocal Phase Shifter
- II. Non-reciprocal Coupler
- III. Magnetoplasmonic Isolators
- **IV. Magnetic Sensor**

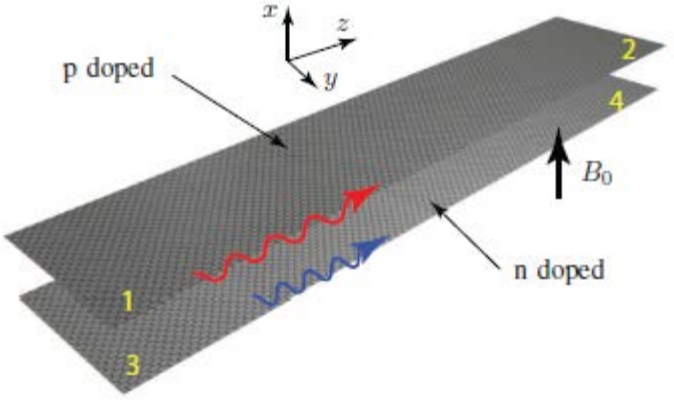
❖ Conclusions & Questions

Broadside Coupled P-N Doped Graphene Strips

chemically doped

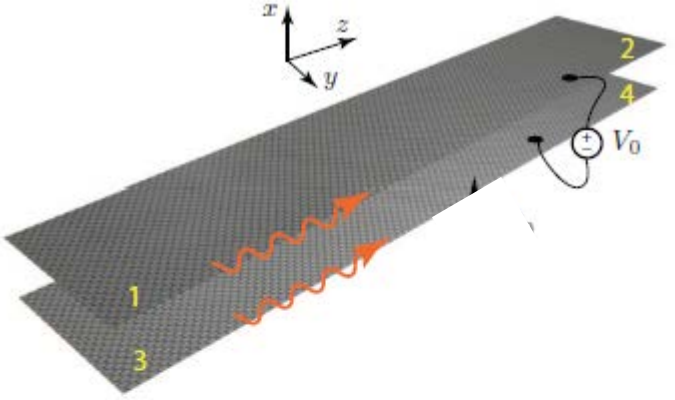


(a)

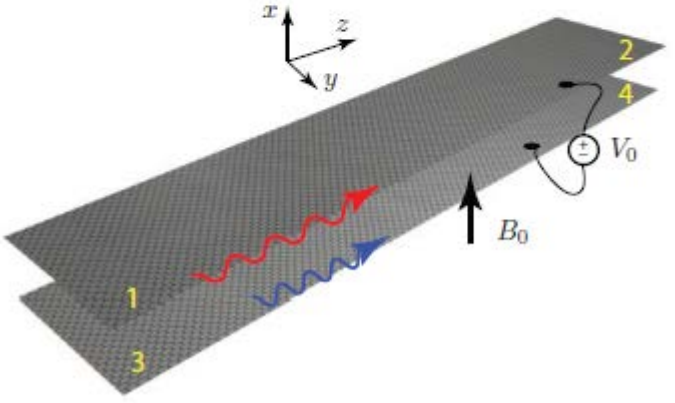


(b)

electrically doped

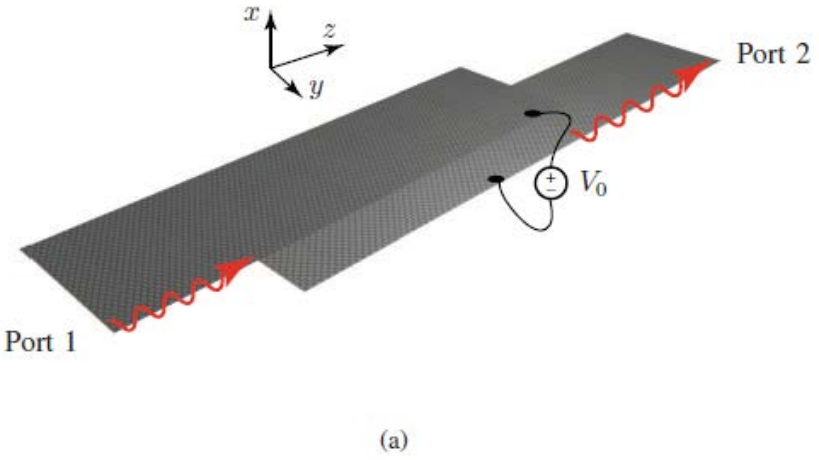


(a)

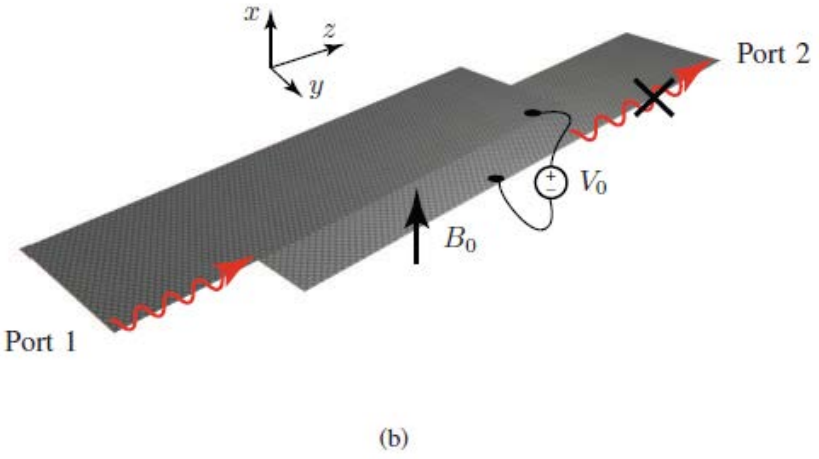


(b)

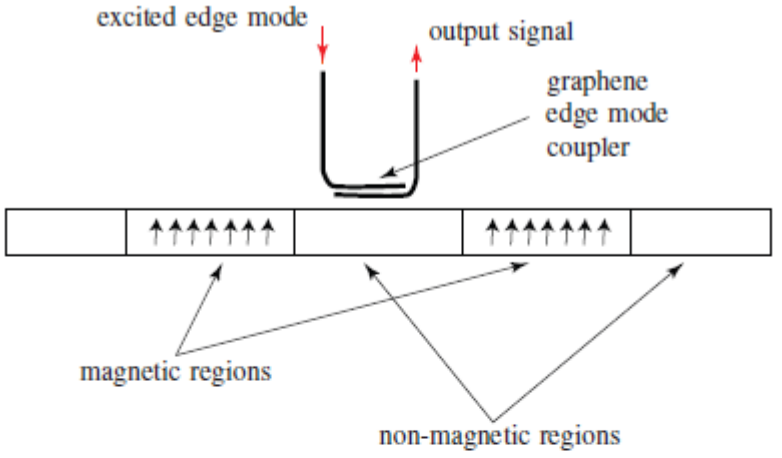
Magnetic Sensor



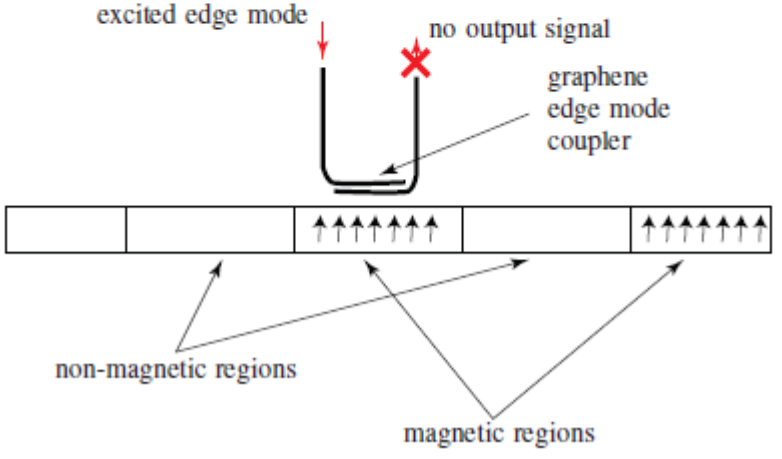
(a)



(b)



(a)



(b)

Outline

I. Introduction to graphene magnetoplasmons

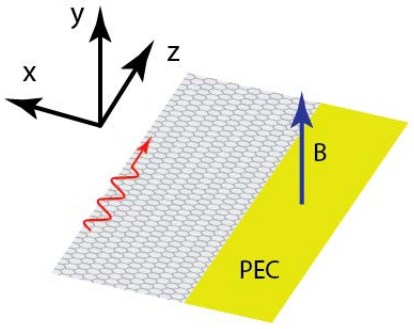
II. Principles of Non-reciprocity

III. Structures and Devices

- I. Nonreciprocal Phase Shifter
- II. Non-reciprocal Coupler
- III. Magnetoplasmonic Isolators
- IV. Magnetic Sensor

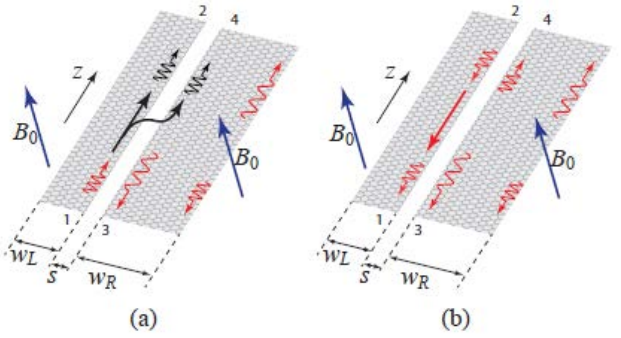
❖ Conclusions & Questions

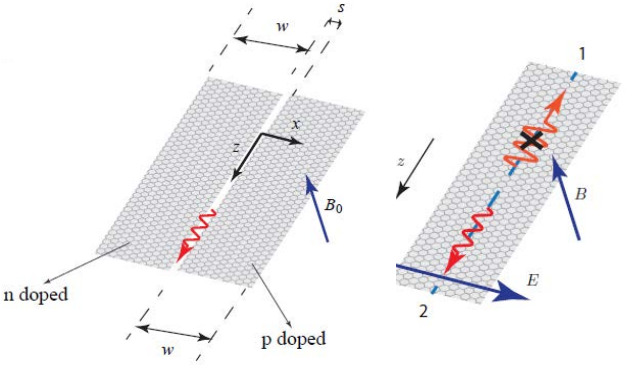
Conclusions



phase shifter

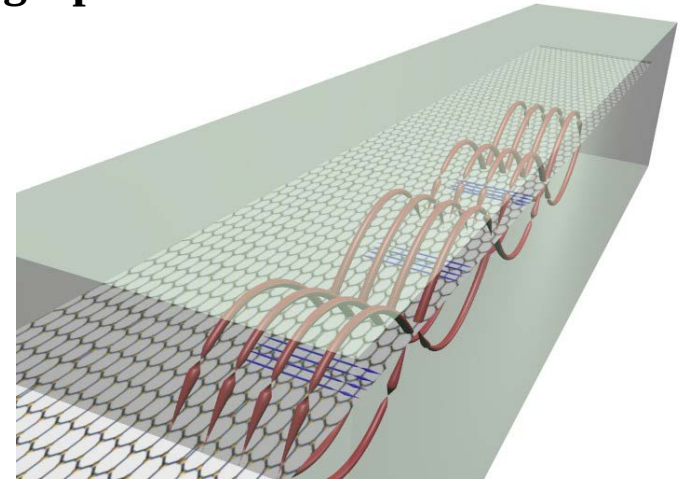
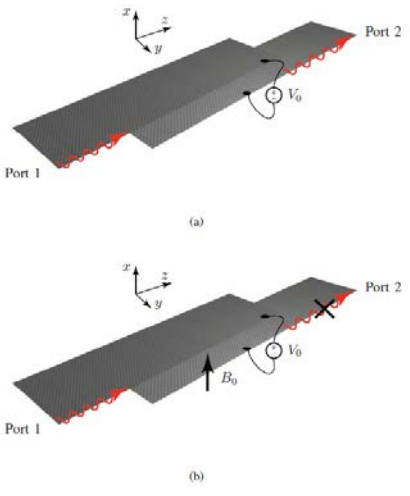
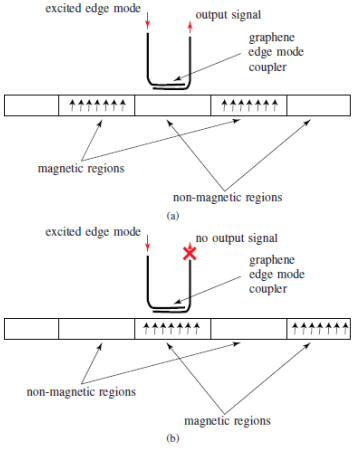
coupler





isolators

graphene-ferrite isolator



magnetic sensor